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GEOLOGICAL MAGAZINE

with which is incorporated

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Founded in 1864 by the late Dr. Henry Woodward, F.R.S.

Edited by

R. H. RASTALL and O. M. B. BULMAN

assisted by

Professor W. S. Boulton
Professor W. G. Fearnsides
Sir Thomas H. Holland
Professor O. T. Jones
Professor C. E. Tilley
Professor W. W. Watts
Henry Woods
Sir A. Smith Woodward

◆

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The Application of the European Time Scale to the Upper Tertiary of North America

By Guy E. Pilgrim

MATTHEW'S provisional classification of the freshwater Tertiary of Western America in 1899 was succeeded ten years later by a detailed correlation of the American Tertiary Mammal horizons with those of Europe, published by Osborn and himself in 1909. At that time these authors placed the Pikermi horizon of Europe (Pontian) in the Upper Miocene and the Val d'Arno horizon (Villafranchian) in the Upper Pliocene. They in common with many later writers subsequently adopted a Lower Pliocene and Pleistocene age respectively for the two horizons named. Allowing for this change of view, Osborn's and Matthew's correlation has been substantially followed, with a few modifications due to individual opinion, by all later authorities. The reasons for it were somewhat elaborated by Osborn in his *Age of Mammals* (1910). It is evident that the Equidae formed the basis for it. The appearance of the genera *Anchitherium* (as species of *Kalobatippus* and *Hypohippus* were then named), *Hipparion* and *Equus* in North America were assumed to be approximately contemporaneous with their appearance in Europe. That North America was at any rate the main, if not the exclusive radiative centre for the distribution of the Equidae has been universally acknowledged. Hence Osborn's and Matthew's choice of this group as a standard of age seemed to be fully justified. In accordance with it the first *Hipparion* beds of North America were regarded as Pontian.

The discovery of *Hipparion* in the Chinji stage of India thus conflicted with the Tortonian age which I had assigned to it.

Matthew, Colbert and others sought to reconcile the inconsistency by denying the Tortonian age of the Chinji and putting it as late as the Upper Sarmatian or Pontian. In a recently published paper (Pilgrim, 1939 *b*), in which the European correlation of the Siwaliks advocated by me was fully demonstrated, it became necessary to explain the appearance of *Hipparion* in India during the Chinji stage (Upper Tortonian) and in America during the Burge and Lower Mint Canyon stages (considered as Upper Sarmatian). Two explanations were suggested :—

(1) That the Burge and Lower Mint Canyon were really contemporaneous with the Chinji and therefore Upper Tortonian, while *Hipparion* did not migrate to Europe until the Upper Sarmatian (1939, p. 468). Even then I thought that this would probably prove to be the true one, but as opportunity did not allow me to examine it fully, I left it as a tentative proposal.

(2) That *Hipparion* arrived in India before it appeared in America. This involved not only a dual origin for *Hipparion*, which still remains, in my opinion, plausible, but also the assumption, which is even more unconventional, that the *Hipparion* stage of Equid evolution in Asia actually predated its development in America. This possibility I admit that I accepted too readily (Pilgrim, 1939 *b*, p. 472). The question asked in the title of that paper I now have little hesitation in answering in the affirmative.

In the case of a family such as the Equidae in which the loss of the lateral digits, the molarization of the premolars, the splitting of the transverse lophs, the increase in hypsodonty and many other well recognized characters have proceeded gradually and regularly on the direct as well as on side lines, it is hardly conceivable that the various developmental stages should have arisen at different times in different places. We may, therefore, postulate that the *Hipparion* stage made its appearance everywhere throughout the world simultaneously or nearly so, whether due to contemporaneous migration or to a multiple origin from diverse species of *Merychippus*. A similar conclusion must be reached in the case of the genera *Hyracotherium* (*Eohippus*), *Anchitherium* and *Equus*.

Naturally there must be two provisos to this postulate : There must exist : (1) an urge to migration ; (2) facilities for migration. The factors causing the first of these have been generally recognized and have been well summarized by Dr. Hopwood in an appendix to my paper in 1939. We cannot, however, assess the extent to which they may have operated at any period in the past. The existence or non-existence of the second, depending as it does on climate or geography, it is possible in some cases, though by no means in all, to predicate with some degree of certainty. The possibility of migration of land animals from America to Europe throughout the Miocene and Pliocene appears to have been taken for granted by Osborn and Matthew when they formulated their ideas about the correlation of the Mammal horizons of these two continents. These authors accepted the appearance of *Hipparion* in the Pontian of Europe as evidence that the American faunas of the Valentine and Republican River in which it first appeared were Pontian. This assumption, however natural at that time, when the Sarmatian and Tortonian land faunas of Asia were unknown, now appears to have been unjustified.

That the complete change in the character of the European Mammalian fauna between the stages of La Grive St. Alban and Pikermi was due to a sudden invasion, chiefly from Asia, has for long been clearly recognized, but so far as I am aware no definite reasons for the phenomenon were ever suggested. The geology of Central Asia, especially of the region east of the Ural Mountains, was very inadequately known thirty years ago. The arrangement of land and water during the Vindobonian period, as conceived at that time, is well shown in the palaeogeographical map published by de Lapparent (1906, p. 1607, fig. 757). In the immense continental area stretching from the Caspian Sea to the Arctic Ocean and uninterruptedly connecting North America with Europe, as drawn in that map, Osborn and Matthew would be unlikely to find any valid reason against a rapidly moving form like *Hipparion*, easily adaptable to any sort of plains environment, migrating to Europe just as soon as it had arrived in Asia from North America.

Later geological surveys (see Geol. Map of U.S.S.R., 1937) have brought out the fact that at any rate up to the Aquitanian a broad sea washed the eastern flank of the Urals and extended to the Caspian Sea. These Palaeogene marine deposits crop out in modern river beds from beneath a Pleistocene fluvio-glacial formation as far north as latitude 64°, but there is little doubt that if the cover could be removed we should find them up to the Arctic Ocean. These are succeeded by Miocene continental deposits ranging from the Aquitanian (*Indricotherium* beds of Bet-pakdala and Turgai) and the Burdigalian (*Brachypotherium aurelianense* beds of Jilancik, Turgai area) up to the Pontian or Upper Sarmatian (*Hipparion* beds of Pavlovdar (Orlov, 1936 *b*), Ischim and Turgai). According to Orlov

(1933, p. 255) during this period there was a retreat of the sea and a gradual transformation of the West Siberian region into a plain which was covered by the drying up remnants of the sea in the form of bays, which were in part united to the Arctic Ocean and equally to the Caspian Sea through the Strait of Turgai, but in part assumed the character of closed basins which by degrees were completely dried up or converted into freshwater lakes.

It is possible that the process thus outlined by Orlov was interrupted by a marine transgression in Western Siberia in the Helvetian and Tortonian corresponding to the increased submergence which is known to have occurred during that period in Europe, Asia Minor, Iraq, Persia and the Caspian (see Haug, 1911, pp. 1682, 1731, 1737). There is, so far as I am aware, no proof either for or against this extension of the sea in the area east of the Urals. However, even in the *Hipparion* fauna of Pavlovdar we may find indications that adjoining the forests where giraffes, deer, antelopes, and carnivora roamed was a country of lakes, rivers, and marshes, which even if it did not pass into an estuary, must have produced an environment extremely unsuitable to a steppe animal such as *Hipparion*. The remains of the last-named, though extremely numerous, may, for all we know, have been brought down by rivers from a country with a drier, steppe climate, which lay much further to the east. The rhinoceroses and beavers, whose remains abound in the Pavlovdar deposits, might be expected to flourish in such an environment. The most conclusive proof of the hypothesis is perhaps to be found in the presence of a primitive seal, *Semantor* (Orlov, 1933, p. 165), which is probably an early side branch of the Phocidae. Matthew's view (1915, p. 224) that the Pinnipeds, of which the Phocidae are the most progressive members, originated in the littoral zone of the Arctic basin of the Old World, is in accord with the idea that the deposits of Pavlovdar were closely connected to the Arctic Ocean.

If the climate and water connections at Pavlovdar were such as Orlov has described in the Pontian, it is likely that during the Sarmatian and Tortonian periods the water barrier east of the Urals was an even more pronounced obstacle to the migration of land mammals and especially of *Hipparion* in a westward direction. Furthermore we cannot at present refuse to admit the possibility that the Pavlovdar *Hipparion* fauna might have predated that of Pikermi, Samos, and Maragha. Even should it prove to show close affinities to the *Hipparion* fauna of China, yet the latter fauna also might not impossibly be somewhat older than Pontian. The presence of species of *Parataxidea*, *Ictitherium*, *Crocuta*, and *Machairodus* (Orlov, 1936 *a*, p. 110; 1939, pp. 527–535), which are close to European Pontian forms, certainly seems to point to a Pontian age for the Pavlovdar deposit. A final answer to this and other questions must, however, await the full description of the Pavlovdar fauna which is not yet available.

It has been shown above that there is an extremely strong probability that the migration of *Hipparion* to Europe by way of the country lying between the Caspian Sea and the Arctic Ocean was definitely prevented by climatic or water barriers or by both, previously to the Pontian. South of this there is proof that the seas of Vindobonian times extended from the northern and southern ends of the Caspian respectively to the Alps, leaving between them a long, relatively narrow tongue of land, linking up the Little Balkan mountains to the Caucasus across the Caspian Sea and continuing through Asia Minor, the Aegean and along the Adriatic to the Alps. These two branches of the Vindobonian Sea united in the Mediterranean, which joined the Atlantic Ocean, thus cutting Europe off both from Africa and Southern Asia. This topography is depicted by de Lapparent (1906, fig. 757, p. 1607). During the Sarmatian, these seas shallowed and in part began to dry up, leaving a large area in Europe and a still larger area round the Caspian occupied by lagoon deposits. It was not until the Pontian that land began to emerge on a large scale, and it would not be surprising that the arrival of *Hipparion* in Western Europe should have been delayed until the latter epoch.

These palaeogeographical conclusions suggest that the land fauna of Eastern Asia and India would have found migration unhindered along the tongue of land mentioned above during the Vindobonian, though it could not actually have reached those parts of Europe, where the well-known Vindobonian mammal deposits of Sansan, Simorre, and La Grive St. Alban occur, so that no interchange of faunas could have taken place between Europe and Asia in the Middle Miocene by this route. On the other hand any mammal deposits of that age situated on the tongue of land in question might be expected to contain either ancestral types of the *Hipparion* fauna of Europe, such as we find in the Chinji stage of India, or forms allied to those of the Middle Miocene of China or America. *Hipparion* itself would also naturally be expected. Unfortunately India even at that epoch seems to have occupied a rather isolated position, while the only indications yet discovered in China of the existence of a mammalian fauna approximately contemporaneous with that of Chinji are the deposits of Tung Gur, Shantung and Kansu (see below, p. 20).

Middle Miocene mammals are even more rare in the strip of ancient land which ran from the Little Balkans to the Alps. In the marine Chokrak beds of the Kuban region, north of the Caucasus, a small number of such fossils have been described (Borissiak, 1928, p. 105; 1929, p. 19; 1937, p. 789; 1938 *a*; 1938 *b*, p. 767). These are *Platybelodon danovi*, *Paranchitherium karpinskii*, and *Dicerorhinus caucasicus*. No affinity to any Indian fossil species exists in any one of these species. *Platybelodon danovi* is, however, closely related to *P. grangeri* of the Tung Gur beds of Mongolia (Osborn, 1936, pp. 459–470). *Paranchitherium karpinskii* shows many points of resemblance to the American genus *Parahippus*, but certain features are shared in common with *Anchitherium*. According to Colbert (1939, p. 6) " the differences between the Chokrak species and *Anchitherium gobiense* from Tung Gur are sufficiently marked to justify the separation of the two forms as distinct types ".

Borissiak (1938 *a*, p. 58) considers that *Dicerorhinus caucasicus* is ancestral to *D. schleiermacheri* of the Pontian of Europe, and that these two forms constitute a different lineage from that which started in the Aquitanian as *D. tagicus* and continued as *D. sansaniensis*. The former lineage is not represented in Europe before the Pontian. Borissiak (1938 *b*, p. 770) does, however, suggest the possibility that a smaller little-known species from the *Indricotherium* beds (Aquitanian) of Bet-pakdala, in W. Siberia, which is much closer to *D. tagicus*, may be the initial stage of the *D. caucasicus-schleiermacheri* line and that its likeness to *D. tagicus* may be due to the fact that both the Aquitanian species are near the branching of two lineages. This evidence, slight as it is, lends no support to any interchange of land faunas between Europe and the Caucasus during the Middle Miocene, though there are indications of eastward migrations.

Before leaving the question of migration routes, I should not omit to touch on one other problem, which concerns the close affinity between certain Indian (Chinji) and Chinese (Tung Gur) forms and those of the Vindobonian of Europe. I am referring especially to the Suid genera *Listriodon* and *Conohyus*, certain Boselaphine antelopes met with in Europe as *Protragocerus chantrei*, *Strepsiportax* (?) *latitrons*, and *Miotragocerus monacensis*, the Chalicotheroid genus *Macrotherium* and the Ursoid genus *Hemicyon*, the last named of which actually found its way into America.

Any explanation as to how these forms were distributed in Eurasia, when as we have seen migration must have been barred to most others, can only be conjectural. One may suppose that an environment such as that of the Ural marshes would be more favourable for the Suidae than for many other families, so that migration would not be impossible. I am, however, inclined to think that most of the genera mentioned reached India and Eastern Asia by way of Africa and Arabia. It may be that communication between Europe and Africa ceased only just previous to the epoch of Sansan, perhaps in the lower Helvetian, and that the European and Asiatic species belonging to the groups in question may be descended from these migrants. It is hardly profitable to pursue the inquiry at this time but I do not consider that the existence of these affinities between European and Asiatic species offers any insuperable objection to the main hypothesis advanced above.

The evidence brought forward in the preceding pages makes it quite unnecessary to suppose that *Hipparion* arrived in Europe at the same time as it reached India, and therefore leaves us free to accept the natural correlation of the Siwaliks, which has been demonstrated in a previous paper (Pilgrim, 1939 *b*). On the assumption that *Hipparion* appeared in North America and India simultaneously or nearly so, it remains to be seen how far the position of the American faunas on the European time-scale can be readjusted so as to harmonize with the facts.

Such a readjustment was made both by J. C. Merriam and Matthew, though their proposals had escaped my notice when I wrote the paper quoted above. Merriam (1919, p. 454) placed the Mascall and Pawnee Creek between the European stages of Sansan and the Sables d'Orleanais ; correlated the Barstow and Santa Fé faunas with that of La Grive St. Alban ; the Thousand Creek, Rattlesnake, and Ricardo with the *Hipparion* fauna of Pikermi, China, and the Siwaliks in part ; and the Blanco with the Lignites of Casino.

Matthew wrote (1924, p. 753) : " These progressive Old World Hipparions appear first at the base of the true Siwalik beds, correlated with the Tortonian. It would appear, therefore, that the entire lower part of the American *Hipparion* zone cannot be later than the Tortonian. The Equidae evidence is supported by other phyla which I will not take time to discuss here. The conclusion would be that the whole of the so-called Lower Pliocene will have to be set back to Upper Miocene, leaving in the Pliocene only the Blanco, Eden and other later faunas."

It is not very clear to me why these two authors suddenly changed their opinion.

It has seemed to me that some of the evidence which led Osborn and Matthew and others after them to adopt the correlation of the American and European fossil faunas which at present holds the field, might be susceptible of a different interpretation in the light of subsequent research. With this object and also in order to obtain any fresh evidence which might bear on the question, I have been studying all the groups of mammals which seem to afford any scope for such a correlation. From its nature this study had necessarily to be conducted for the most part second-hand, even were actual specimens available, which was seldom the case. Descriptions and figures of the various mammal species are, however, now so full and have been confirmed in so many quarters, that the results are readily understandable and trustworthy.

Unfortunately on account of geographical distance and other reasons few American forms are comparable with those which occur in Europe and hardly more so with Indian ones. Western Asia and China seem likely to afford a closer parallel to America and this is apparent in the case of Eocene and Oligocene faunas and in those of Pontian and later periods. The Miocene faunas of China are, however, almost completely unknown, except for the glimpses afforded by the deposits at Tung Gur, Kansu and Shantung. The region of Bet-pakdala in Western Siberia may give us important information (see Flerov, 1938, p. 94), but the full description of this fauna is as yet unpublished.

During the last thirty years additional information on the Upper Tertiary Mammalian deposits of North America has accumulated apace, and the relation in which the various faunas stand to one another has been more exactly determined than when Osborn and Matthew wrote in 1909. The stratigraphical succession of the main mammal faunas may in fact be regarded as fairly certain. Doubt is admissible only as to the intervals of time which each fauna occupied and which separate them from one another. Differences of opinion as to the amount of time overlap between one section and another, and as to whether diversities of fauna in different sections are due to time mutations or to geographical distance or environment, are unavoidable.

Of recent years several correlations of the American faunas have been formulated by authorities of note. H. J. and M. C. Cook (1933) correlated the Tertiary vertebrata of Nebraska and adjacent areas in a valuable paper accompanied by faunal lists and a European time scale. G. G. Simpson (1933) compiled a comprehensive glossary of all the North American Mammal-bearing formations with charts arranged on the European time scale, and a list of literature Stirton (1936) has published lists of all the North American so-called Pliocene Mammalian faunas, arranged in their most probable succession, and tables showing the distribution of the various genera throughout them ; a useful list of literature is appended. I have been greatly indebted to all these authors and to numerous others, whose names and publications it is impossible to quote here. Differences it is true exist between their views, but the main succession is the same and this I have naturally accepted, merely attempting to space out the various faunal stages between the points which in my opinion afford the most likely datum lines of correspondence with Europe.

I shall endeavour to show that all the North American faunas from the John Day up to the Hay Springs and Irvington fit in well to the correlation scheme which I now suggest and which is tabulated in the chart on pp. 10, 11. The numerous stages or sub-stages into which I have divided the geological succession does not imply that the correlation makes any pretence at being more than approximate, but have been used partly because that is the only means by which I can take account of the large number of American faunas and partly because the system names Miocene, Pliocene, and Pleistocene have at present no meaning since they have not been employed by every writer in the same sense. The changes involved hardly affect the generally accepted correlation of formations older than the Harrison, and mainly concern those which extend from the Sheep Creek to the Hagerman and Blanco. Nevertheless it may be as well to include the White River and John Day in my summary of the evidence which bears on the question, in order to demonstrate that my correlation is, as I hope, consistent throughout.

It will first be convenient to review the evidence for the correlation of the White River formation. Here and throughout this paper I lay the chief stress on the first appearance of similar forms in the Old and the New World and none at all on their extinction, which is unlikely to have been simultaneous in widely separated regions.

The Anthracotheriidae have been considered as most valuable for this purpose. Numerous Anthracotheroid species which were originally referred to the European genus *Ancodus* occur in the White River formation, first appearing as the species *A. americanus* in the Titanotherium beds and represented by other species right up to the top of the White River group.

EQUIVALENT MAMMAL FAUNAS

CONTINENTAL ZONE FOSSILS	DAKOTA	NEBRASKA	TEXAS NEW MEXICO	NEVADA
Bison, Ovibos reach America *Elephas primigenius* Europe				
Elephas columbi America *Elephas trogontherii* Europe	Hay Springs		L. Rock Creek	
First Equus *Elephas planifrons* and *meridionalis*				
Plesippus. Elephas appears in India		U. Snake Creek (in part)	Blanco	
Agriotherium *Indarctos, Simocyon, Parataxidea, Plesiogulo, Eomellivora, Machairodus*		U. Snake Creek (in part)	Hemphill	Thousand Cre
			Clarendon	Fish Lake Vall
	Valentine (restricted) Minnechaduza	U. Snake Creek (in part)		
First *Hipparion*	Burge			
Hemicyon reaches America *Platybelodon* appears	Niobrara R.		L. Santa Fé	L. Cedar Mounta
Hemicyon appears in Europe First *Merychippus*		L. Snake Creek Sheep Creek		Virgin Va
		U. Harrison		
Brachypotherium aurelianense First *Anchitherium*	U. Rosebud	L. Harrison		
First *Moropus* *Indricotheriinae* appear *Ancodus, Bothriogenys, Bunobrachyodus, Aepinacodon*	L. Rosebud	Monroe Gehring		
Subhyracodon tridactylum *Diceratherium armatum*		Protoceras beds White River Group		
Subhyracodon occidentale		Oreodon beds		
Subhyracodon trigonodum		Titanotherium beds		
Anthracotherium, Anthracokeryx			Duchesne or U. Uinta (Utah)	
			Bridger (Wyoming)	

UROPE, ASIA, AND NORTH AMERICA

ARIZONA	CALIFORNIA	OREGON IDAHO	CHINA W. SIBERIA	INDIA	EUROPE
	Rancho La Brea	American Falls		Boulder Congl.	Post-Cromerian
	Irvington				Cromerian (Forest bed) Cromer.
U. San Pedro (Curtis)			Nihowan	Pinjor	Villafranchian (Val d'Arno, Senèze)
	Tehama	Hagerman	*Mastodon borsoni* and *Antilospira* beds of S.E. Shansi	Tatrot	Astian (Montpellier)
L. San Pedro (Benson)					Plaisancian (Casino)
	Mt. Eden Kern R.	Rattlesnake	Red *Hipparion* beds of China. Pavlovdar (W. Siberia)	Dhok Pathan	Pontian (Pikermi)
	Etchegoin			Nagri	U. Sarmatian (Sebastopol, Czakvaz)
	U. Chanac U. Ricardo U. Mint Canyon				L. Sarmatian (Vienna basin)
	L. Ricardo L. Chanac		Tung Gur Shantung	Chinji	U. Tortonian
	L. Mint Canyon Barstow		*Paranchitherium* beds of Chokrak	Kamlial	L. Tortonian (Simorre, La Grive St. Alban)
		Mascall		Murree	Helvetian (Sansan)
					U. Burdigalian (Faluns de Touraine, Romieu)
			Jilancik (Turgai)	Fatehjang	L. Burdigalian (Sables d'Orleanais)
		U. John Day M. John Day	Bet-pakdala (W. Siberia) Hsanda Gol		Aquitanian (St. Gerand Le Puy, Pyrimont)
		L. John Day			Chattian (Coderet, Peu Blanc)
					Stampian (Cournon)
					Sannoisian (Ronzon, Hempstead)
			Irdin Manha	Pondaung	Ludian (Euzet les Bains)
				L. Chharat	Lutetian

They have not been found in the John Day though another species, *A. leptodus*, occurs in the Lower Rosebud. It has been shown (Stehlin, 1929, p. 611) that the American forms have more mesaxonic front feet than *Ancodus* or any of the other Old World phyla which have been separated under the names of *Brachyodus*, *Bunobrachyodus*, *Bothriogenys*, and *Anthracotherium*. Troxell (1921, p. 334) has noted other differences and has separated them under the generic name of *Aepinacodon*. *Anthracotherium* appears earlier than the other lineages and differs more widely. The others have teeth which, though they differ in certain ways, agree as to their general evolutionary stage. The European and African phyla appear approximately at the same time in the Sannoisian.

We have some grounds for thinking that the centre of distribution for the family lay in South-Eastern Asia. In Burma the genera *Anthracokeryx* and *Anthracothema* are in a decidedly more primitive stage than any of those mentioned above. The beds in which they occur are probably Ludian. It seems likely that the American *Aepinacodon* equally with the European and African Sannoisian genera were derived from one of the Burmese Ludian genera, and since the supposed radiative centre is equally distant from the regions in which their successors first appear, it is probable that the American migrant reached the New World simultaneously or nearly so with the migrants to Africa and Europe. This indicates an approximate Sannoisian age for the *Titanotherium* beds of the White River. This does not of course give us any information as to the age of the upper *Protoceras* beds, but the rate of evolution of the autochthonous White River faunas is of an order which might be expected to embrace at least the three European stages, Sannoisian, Stampian, and Chattian. The occurrence of the same species *Diceratherium armatum* in the Lower John Day of Oregon and the *Protoceras* beds of the White River of Dakota may be taken to indicate that these two sets of beds may be correlated (H. E. Wood, 1927, p. 71 ; 1929, p. 73 ; 1933) ; the Lower John Day is unfortunately almost barren of fossils.

Osborn (1910, pp. 191, 197, 226, 228) has stressed the appearance of the Rodent genus *Palaeocastor*, which he supposed to be congeneric with the European *Steneofiber*, in the *Protoceras* beds of the White River and its abundance in the Middle John Day, as compared with the first European appearance of *Steneofiber* in the Aquitanian of St. Gerand Le Puy. Schreuder (1929, p. 279 ; 1931, p. 165), however, showed that the American *Palaeocastor nebrascensis* with its short limbs, brachycephalic skull and adaptations to a fossorial and terrestrial rather than to an aquatic life, belongs to an entirely different phylum from the European *Steneofiber*. An equal doubt seems to exist as to whether *Eucastor* of the Valentine stage and its descendants of the Rattlesnake are closely allied to *Dipoides* of Eurasia (Schreuder, 1929, p. 287 ; 1931, p. 168). The Castoroidea are evidently divisible into several lineages, the phylogenetic connection of which to one another is at present obscure, so that the family cannot be said to afford the satisfactory basis for correlating American and European faunas which Osborn and others have supposed.

The Middle and Upper John Day afford much more definite evidence for a close correspondence with Europe. The most important is that derived from the Anchitherine stage of Equid evolution. The European species *Anchitherium aurelianense* Cuv. was founded on specimens from the Sables d'Orleanais taken as Lower Burdigalian in age. No ancestral form exists in the Aquitanian beds of St. Gerand Le Puy or Pyrimont. Nor indeed does any Equid occur in Europe between the early *Hyracotherium* of the Lower Eocene and *Anchitherium*. This genus is, therefore, an immigrant to Europe. Towards the end of the last century several American Equid species were referred to *Anchitherium*. Here the case is very different ; an extremely gradual transition exists between *Mesohippus*, which ranges through the White River formation, *Miohippus* of the Upper zones of the White River, the John Day and later, and what may be described as the *Anchitherium* stage of Equid evolution (see Matthew, 1926). No region between America and Europe affords any evidence as to the nature and progress of the migrants, but that the migration must in the first instance have started from America seems certain.

The American Anchitherine species have been generically separated from *Anchitherium* under the names of *Kalobatippus* and *Hypohippus*. *K. praestans*, which occurs at the top of the John Day, is the earliest of these. Though agreeing with *Anchitherium* in most of its characters as Romer (1926) and Wehrli (1938) have shown, yet it differs from the European genus both by its less reduced last molar and by its long slender limbs. *K. agatense* from the Lower Harrison is a larger, more advanced species than *K. praestans* and is somewhat closer to *Anchitherium* in both the characters named above. *Hypohippus* possesses the short limbs of *Anchitherium* but differs in the slight development of a parastyle in P ^{2}. *Hypohippus* and *Kalobatippus* are considered by Romer (1926) and Wehrli (1938) to be generically inseparable from *Anchitherium*, both branches being derived from *Miohippus*. It seems probable that *Anchitherium* represents a third branch derived from a migratory species of *Miohippus*, since it is impossible to suppose that the long-limbed *Kalobatippus* gave rise directly to *Anchitherium*. In any case *K. praestans* cannot be later than the Lower Burdigalian, since it is assumed that the Anchitherine stage cannot have appeared in Europe before it arose in America. This argument does not exclude the possibility that *K. praestans* in America may predate *Anchitherium aurelianense* in Europe, which will give us an Aquitanian age for the Upper John Day. American writers have favoured, some the one, some the other age for the Upper John Day.

Additional evidence is afforded by other groups of mammals. Osborn has already made use of the Diceratherine rhinoceroses in this connection. *Diceratherium* occurs plentifully throughout the John Day, represented by several species, and persists into the Upper Harrison and the Upper Rosebud. It also occurs in the *Protoceras* beds of the White River, one species, *D. armatum*, being identical with the type from the Lower John Day. This according to H. E. Wood (1929, p. 73) indicates that the Lower John Day is roughly equivalent to the *Protoceras* beds. Osborn (1900, p. 232; 1910, p. 198) assumed that the European species *Diceratherium pleuroceros* from Gannat (Chattian) and *D. asphaltense* from Pyrimont (Aquitanian) were congeneric with the American *Diceratherium*, and indicated an identity of age. Borissiak (1927, pp. 779–785) showed that the abbreviation of the limbs in the European species as well as other characters provided a generic distinction alike from the American *Diceratherium* and from forms like *Aceratherium lemanense*. Wood (1929, p. 73) resuscitated Rogers's name of *Pleuroceros* for the European Diceratheres. Osborn (1898, p. 163; 1910, p. 227) clearly recognized direct ancestral types of the true *Diceratherium* in the White River beds with rudiments of the paired horns; Wood has confirmed this and has referred them to the genus *Subhyracodon*. These pre-Diceratherc species are *S. trigonodum* from the *Titanotherium* beds, *S. copei* and *S. occidentale* from the *Oreodon* beds, and *S. tridactylum* from the *Protoceras* beds (see Wood, 1927, pp. 59–71). These facts indicate (1) that *Diceratherium* was endemic in America, and (2) that *Pleuroceros* was a migrant to Europe. If we assume that this paired-horn Rhinocerotid stage arose simultaneously in the Old and the New World, it indicates that the Lower John Day cannot be later than Chattian, and then only if we suppose that a Sannoisian or Stampian migratory species of *Subhyracodon* wandered into the Old World. The situation is then very similar to that of the Anchitheres, except that with regard to the Diceratheres there is an element of doubt as to whether the paired horns may not have developed quite independently on distinct phyla.

The two lineages so far considered had their origin in North America and thence migrated to Europe. Another group which seems to offer evidence for correlation is that of the Chalicotheroidea. The earliest known Chalicotheroid genus is *Eomoropus* of the Uinta, but the next appearance of the order in America is not until the John Day as *Moropus*. Colbert's (1935 *a*, p. 14) suggestion that the order originated in America, migrated to Asia, where its development proceeded, and later returned to America, seems rather far-fetched. Not only is *Eomoropus* found in the Irdin Manha of Mongolia (Ludian) but other Chalicotheroid genera, *Grangeria* and *Olsenia* also occur there. Against the absence of Chalicotheroids in the American Oligocene, *Schizotherium* is present in beds of this age both in Europe and Asia. *Moropus* has been recorded in the *Indricotherium* beds of the Bet-pakdala region (Aquitanian), associated with the American genus *Colodon* and numerous Anthracotheriidae (Flerov, 1938, p. 94) though the remains have not as yet been fully described. An allied, possibly generically identical form, occurs in the Lower Burdigalian of India as *Phyllotillon naricus*. Even if the Uinta is slightly earlier than the Irdin Manha, it seems far more likely that the radiative centre of the Chalicotheroidea was Asiatic throughout, and that their occurrence in America was due to emigration. Little is known of the John Day species *Moropus senex*, *M. distans*, and *M. oregonensis*, though they are much smaller than *M. elatus* of the Lower Harrison, and agree in size with *Phyllotillon naricus* of the Lower Burdigalian of India. It is possible that *Moropus*, though appearing in the Aquitanian of Bet-pakdala, reached both India and America simultaneously in the Lower Burdigalian, but it is more likely, apart from the possibility that *Moropus* or *Phyllotillon* may have existed in the still unknown Aquitanian of India, that America received these migrants in the Aquitanian, being more accessible than India.

Originally Osborn (1909, p. 77) thought that the Amphicyoninae were migrants from Europe to America, and was inclined to attribute the occurrence of species of *Amphicyon* in the Deep River and Sheep Creek beds to a migration much later than the Sables d'Orleanais where species which resemble them in dental characters occur. Matthew (1924 *a*, p. 106) and others, however, have shown (1) that the American *Amphicyon* is directly descended from *Daphoenodon* of the Harrison and *Daphoenus* of the White River ; (2) that the Amphicyoninae are a polyphyletic stock and that owing to their poorly represented remains in Europe it is impossible with certainty to affiliate the forms which occur in the two continents.

One Canid form does, however, seem to afford some ground for correlation. This exists in the species *Haplocyon crucians* from the Aquitanian of St. Gerand le Puy and *H. dombrowskii* from the Chattian of La Milloque. Helbing (1928, p. 36) first pointed out the close affinity between the latter species and *Temnocyon altigenis* from the Middle John Day. Viret (1929, pp. 126–8) confirmed this in the case of *Haplocyon crucians*, and even suggested that they might be merely two subgenera of the same genus.

The evidence as a whole seems to favour an Aquitanian age for the Middle and Upper John Day, but at any rate if the Upper John Day were astride of the Burdigalian and Aquitanian stages it would be consistent with the opinions which various authorities have expressed on the subject.

Above the John Day series and probably separated from it by an erosion unconformity are the thick Columbia Lavas. These pass into the Mascall mammal-bearing beds, again with a probable slight unconformity. A much greater and more marked unconformity separates the Mascall from the Rattlesnake. The Mascall fauna may be correlated fairly certainly with the Lower Snake Creek fauna of Nebraska. We have now to consider the faunas which are likely to fill up the gap between the John Day and the Mascall. There is fairly general agreement that these include all or part of the Sheep Creek, the Harrison (with the Monroe Creek and Gehring at their base) and the Rosebud. Opinions, however, differ as to how far the lower portion of these beds is contemporaneous with the John Day as well as to what exact part of the European sequence they correspond. We may provisionally accept the stratigraphical position assigned to these faunas by H. J. and M. C. Cook (1933, p. 44) which is as follows in descending order.

Lower Snake Creek = Mascall
Sheep Creek
Upper Harrison
Lower Harrison = Upper Rosebud
Monroe Creek and Gehring = Lower Rosebud = Upper John Day

The Lower Rosebud contains *Promerycochoerus*, *Mesoreodon*, and *Leptauchenia*, which characterize the Upper John Day. The first of these genera persists into the Lower Harrison as *P. vantasselensis*, but does not occur in the Upper Rosebud. The other two are absent from both. *Parahippus* appears to have existed in the Lower Rosebud and *Kalobatippus* in the Lower Harrison, but as a species *K. agatensis* which is larger and more advanced than *K. praestans* of the Upper John Day. *Moropus elatus* of the Lower Harrison is much larger and apparently more advanced than either *M. senex* and *S. distans* from the John Day or *Phyllotillon naricus* from the Bugti Hills of India (Lower Burdigalian). In both the Upper Harrison and the Upper Rosebud *Promerycochoerus* is replaced by *Merycochoerus*.

In the Sheep Creek fauna we first meet with the genus *Merychippus* and undoubted representatives of the Merycodine branch of the Antilocapridae. The latter have been recorded by Cook (1933, p. 37; 1934, p. 161) in the Upper Harrison, though Frick (1937, p. 287, footnote) considers the identification as doubtful.

Many forms testify to the contemporaneity of the Mascall and the Lower Snake Creek. According to Cook the Pawnee Creek is slightly older, perhaps Upper Sheep Creek. This horizon is marked by the arrival of the Proboscidea and the Teleocerine Rhinoceroses in America, as well as forms like *Dromomeryx* which may possibly belong to the same family as the European *Palaeomeryx*. Osborn (1909, p. 77) has commented upon the fact that these three groups appear first in the Lower Burdigalian of Europe in the following words: " Homotaxis with Europe is provisional owing to uncertainty as to the speed or rate of migration from Europe. The new mammals of this stage (viz. Proboscidea, Teleocerinae, and Pecora are all from Europe, where they form the chief characteristic of the Lower Miocene; but we may suppose that these animals occupied a portion of the Lower Miocene period in migrating from Western Europe to North America."

Apparently we are faced with a choice as to whether we shall correlate with the Lower Burdigalian of Europe the Upper John Day containing Anchitherine Equidae, Diceratherines and *Moropus*, or the Pawnee Creek containing the forms just mentioned. The choice is, however, less difficult than appears at first sight for the following reasons. In the first place Hopwood (in Pilgrim, 1939, appendix, p. 472) has shown by his studies on the emigration of Proboscidea from India that as a class they are much less prone to leave the country of their origin immediately than other rapidly moving animals, especially the Equidae. In the second place it is not always easy to decide to which Proboscidean lineage certain species belong, on account of the convergent development of similar dental characters.

Consequently a comparison between two species which may not after all belong to the same phylum is apt to be dangerous. In some cases, however, it seems clear that the Pawnee Creek Proboscidea are in a later stage of development than their ancestors of the Lower Burdigalian of Europe. Thus *Miomastodon merriami* of the Virgin Valley and Pawnee Creek is more advanced than *M. depereti* of the Sables d'Orleanais (Osborn, 1936, p. 693).

Osborn's remarks quoted above were based on the assumption that the various short-legged Rhinocerotid types found throughout Europe and Asia were congeneric with *Teleoceras fossiger* of the American Republican River and *Mesoceras medicornutus* of the Pawnee Creek. Ringström (1924, pp. 26, 66–74) pointed out that the Asiatic and some of the European forms were referable to a new genus *Chilotherium*, which was quite distinct both from the American Teleocerines and also from the European supposed Teleocerines which occurred first as *Brachypotherium aginense* of the Aquitanian and *B. aurelianense* of the Lower Burdigalian. Matthew (1931, p. 2) denied that the true *Teleoceras* has anything especially in common with *Brachypotherium* except the short legs. He placed the latter genus on an early side branch coming off from the main stem leading to *Teleoceras*, while *Chilotherium* is even more remote, on a side branch from *Aphelops*. These forms, therefore, seem to possess no definite value for correlation between Europe and America.

The Cervidae afford no greater scope for correlation, since the material of most of the early European forms is so fragmentary that affinities with American forms are quite conjectural. Similar types of antler may have arisen quite independently and on different lineages at epochs which are far removed from one another.

Somewhat more definite inferences may in my opinion be drawn from the Antilocaprinae. One can hardly doubt, when one studies their skull, skeletal, and dental structure, that they represent an early, highly specialized branch of the Aegodont Bovidae (see Pilgrim, 1939, pp. 20, 26). The earliest appearance of the Merycodine branch of this subfamily in America is in the Sheep Creek, or Upper Harrison, if Cook's determination is correct. Since it is preceded by no ancestral form in America, it must be a migrant, and if so its origin can only have been in Asia. Outside America the only form which has been ever referred to the group is *Heterocemas simpsoni* from a Miocene deposit in Shantung described by Young (1937, p. 228). The size, shape, and burrless character of the horn figured by Young seems to indicate that it belongs to a developmental stage more progressive even than *Meryceros* of the Barstow and Niobrara River. The age of the Shantung fauna seems to be nearly the same as that of Tung Gur (see below page 21). Considering the almost entire absence of Lower and Middle Miocene mammal faunas in China, it is not surprising that no other traces of the Merycodinae should have been found. Its subsequent extinction in the country of its origin is more surprising but not impossible. The high state of development reached in the case of one Aegodont subfamily at least, the Caprinae, in the Tung Gur period (probably Upper Tortonian, see below page 21) argues at latest a Helvetian or more probably a Burdigalian age for the separation of the Merycodinae from the various Aegodont subfamilies. The existence of a primitive Bovid, *Eotragus*, which may belong to the Boodont branch of the family, in the Helvetian of Sansan and of Lake Victoria Nyanza in East Africa (see Pilgrim, 1939 *a*, p. 25) is an additional proof of this. The migration to America may of course have been later than this, but must have been earlier than the Tung Gur epoch. On the whole Helvetian seems to have been the most likely age for the Sheep Creek. I hesitate to put the Sheep Creek further back than this because it would involve us in difficulties with the various faunas which serve to fill in the geological interval between the Sheep Creek and the Upper San Pedro. Most of these do not differ greatly from one another and one could hardly imagine them as covering a longer interval than that embraced between the Helvetian and the Villafranchian.

Mention may here be made of the fragmentary mandible from the Pawnee Creek provisionally referred by Frick (1926, p. 106) to the European genus *Ursavus*. This identity if substantiated would be evidence of a Helvetian or Tortonian age for the Mascall horizon.

It will thus be realized that from the top of the John Day to the Lower Snake Creek we have no direct faunal evidence bearing on the European correlation, and we can only space out the American faunas, of which the stratigraphical succession is fairly certain, between the top of the John Day and the Barstow and Santa Fé faunas, where we next encounter forms belonging to the Ursidae which may be directly compared with those of the Old World. Merriam (1919, pp. 450–5) clearly showed that the fauna of the Barstow (California) and the Lower Santa Fé (New Mexico), although still containing *Merychippus* in abundance and without *Hipparion*, is distinctly newer than the Mascall and Pawnee Creek and older than the

Ricardo. The Barstow and Santa Fé faunas have been much increased by collections made since Merriam first studied them, and the complete results are not even now available. McGrew and Meade (1938, p. 197) have divided the beds in the Valentine area of Nebraska into faunal zones and have correlated them with California. They give the name of Niobrara River to a stage which they consider is the equivalent of the Barstow, and have erected a new stage, the Burge, which corresponds to the Ricardo and occupies an intermediate position between the Niobrara River and the Valentine (restricted).

The Ursidae seem to have originated and developed in the Old World, whence several genera migrated to America, apparently as they arose, since there is no evidence of a dual origin. Examples of these migrants are *Hemicyon*, *Indarctos*, *Agriotherium*, *Ursus*, and possibly *Ursavus*. *Hemicyon* appears in the Helvetian of Sansan as the species *H. sansaniensis*. It also occurs at Göriach, probably of the same age as Sansan, as *H. göriachensis ;* continues in the Tortonian of La Grive St. Alban as *H. grivensis*, and persists into the Sarmatian of Stätzling as *H. stätzlingii*. The genus occurs in the Santa Fé as *H. ursinus* and in the Barstow as *H. barstowensis* and *H. californicus* (see Frick, 1926, pp. 18–53). The Barstow and Lower Santa Fé cannot, therefore, be older than Helvetian, and since the American species are more advanced than at least one of the Helvetian species on account of the entire absence of a parastyle in P^4, it seems more reasonable to correlate the American beds with the Tortonian.

Yet another species of *Hemicyon*, *H. teilhardi*, has recently been described by Colbert (1939, p. 47) from the Tung Gur deposits of Mongolia. Though a large species, showing all the typical characters of *H. ursinus*, it exhibits certain peculiarities in the size of the bulla, the width of the upper molars, and the angle of the mandible, which indicate specialization. These are not inconsistent with a slightly later date than Barstow and Santa Fé for the Tung Gur beds.

In this connection it may be worth while to review the evidence for the age of Tung Gur. *Platybelodon grangeri* is directly comparable to *P. danovi* of the Chokrak beds of the Caucasus, which according to Borissiak (1928, p. 105) are Middle Miocene. A collateral branch of the same family, less specialized mechanically, is known under the name of *Toreunobelodon barnum browni ;* it occurs in the Valentine area of Nebraska and is probably later in age than Tung Gur (see Osborn, 1936, pp. 459–470). *Serridentinus gobiensis* from the same deposit at

Tung Gur is stated by Osborn (1936, p. 398) to be in the same evolutionary stage as *Serridentinus subtapiroides* from Eibiswald, taken as Helvetian in age.

Anchitherium gobiense is a large species closely comparable, according to Colbert (1939 *a*, p. 5), with the Helvetian and Tortonian varieties of *Anchitherium aurelianense* and less advanced than the Pontian Chinese species *Anchitherium* (*Hypohippus*) *zitteli*. The same author (Colbert, 1934 *b*, p. 374) considers that two species of *Macrotherium* show affinities to *M. grande* of La Grive St. Alban and *M. salinum* of the Chinji stage of India.

A *Listriodon*, *L. mongoliense* (Colbert, 1934 *a*) is closely allied both to *L. elegans*, the Vindobonian species of Europe as well as to *L. pentapotamiae*, of the Chinji stage of India. These species persist into the Pontian of Europe and the Dhok Pathan of India respectively, but in both areas they are more typical of the Tortonian. Cervidae occur ; they include *Dicrocerus* (?) and a new form *Stephanocemas* referred by Colbert (1936) to the Cervulinae. A large species of the Giraffoid, *Palaeotragus*, is fairly plentiful (Colbert, 1936 *b*) though the skull is imperfectly preserved. It shows affinities both to *P. expectans* of Sebastopol and *Giraffokeryx* of the Chinji stage of India. *Oioceros* is a well-known Pontian genus of Europe and Maragha, but the Tung Gur species *O. grangeri* and *O. noverca* (Pilgrim, 1934) are distinctly more primitive than the Pontian species. Many Carnivora occur (Colbert, 1939 *b*) ; among them are *Amphicyon*, *Machairodus* (?), *Crocuta tungurensis*, close to *C. carnifex* of Chinji, which is ancestral to *C. eximia* of the Pontian. According to A. E. Wood (1936) the Rodent fauna of Tung Gur indicates the possibility of an age which may predate the Upper Miocene. The occurrence of a species of *Amblycastor*, which Stirton (1934) considers is closely related to *A. fluminis* of the Lower Snake Creek, is very significant.

On the whole it seems that an age slightly later than that of La Grive St. Alban and approximately contemporaneous with that of Chinji is the most probable. It is true that *Hipparion* which occurs at Chinji is absent from the Tung Gur fauna, which may indicate an epoch earlier than the appearance of *Hipparion*. On the other hand *Merychippus*, the ancestral stage of *Hipparion*, is equally absent. An explanation of the absence of these two steppe horses may perhaps be found in the fact that Tung Gur is essentially a forest and not a plains fauna.

The Miocene fauna of Shantung described by Young (1937, p. 209) is meagre, but contains the Cervid genus *Stephanocemas*, and horns which Young has referred to an Antilocaprid

(*Heterocernas*). It is probably of the same age as that of Tung Gur.

The Burge, Lower Mint Canyon, and Ricardo faunas are obviously later than that of the Barstow, because of the presence of *Hipparion*. As I have endeavoured to show on page 2 the first appearance of *Hipparion* in the Burge and Lower Mint Canyon of America and the Chinji stage of India affords not merely valid but strong evidence for correlating them, a fact on which most American authorities have strongly insisted. No form whatever gives any proof of a contemporary exchange of faunas between Europe and America, but the peculiar distribution of land and water in pre-Pontian times explained above (pages 3–5) is, in my opinion, entirely adequate to prevent the travel of land animals between Europe and Asia.

Yet one other argument in favour of the correlation which I advocate is to be found in the existence of a fossiliferous marine formation, the Modelo, overlying the Mint Canyon beds. This has been regarded as Upper Miocene on the evidence of the proportion which the number of extinct species bears to that of living species (see Maxson, 1930, pp. 79, 80 ; Kleinpell, 1938, pp. 71, 160–181 ; and Stirton, 1939, pp. 135, 136). This position has been denied by most American vertebrate palaeontologists who have regarded the Mint Canyon fauna as Pliocene.

The fauna which immediately succeeds the Burge equally shows no correspondence with Europe, nor even with the Nagri stage of India except for the presence of *Hipparion* and *Heterofelis catocopis*, which latter may be descended from forms in the Chinji of India. Most American writers agree that faunas such as the Valentine, Republican River, and Upper Snake Creek differ little from one another, but their exact succession and the upper age limits of some of them are in doubt.

There is a general consensus of opinion that the Rattlesnake fauna is distinctly later than the Valentine. With the Rattlesnake I include, without expressing an opinion as to their exact equivalence to the Rattlesnake or to one another, the Thousand Creek, Hemphill, Eden, Edson, Smoky Hill River, and Kern River. In this stage for the first time since the Barstow we have a close correspondence with Europe. A series of Carnivora belonging to the genera *Indarctos*, *Simocyon* (*Araeocyon*), *Taxidea* (*Parataxidea*), *Plesiogulo*, and *Eomellivora* show specific affinities to forms which are distributed through the Pontian of Europe and Central Asia and the Dhok Pathan stage of India. One can hardly doubt that their presence in America is due to direct contemporaneous migration, and in my opinion affords the strongest proof that the Rattlesnake and the equivalent beds may be correlated very nearly with the Pontian.

The failure of Pontian forms belonging to other zoological groups such as the Bovidae, Cervidae, Suidae, Rhinocerotidae, and Proboscidea to migrate to America in the Rattlesnake period and of the Antilocaprinae to travel in the reverse direction can only be explained conjecturally. The passage between the two continents could have taken place only by an arctic route and this may have offered insurmountable difficulties for most of the fauna. Even at a later date migration of the Rhinocerotidae, Suidae, Bovidae, and Antilocaprinae either did not occur at all or only sparsely.

It only remains to distribute the faunas between the Burge and the Rattlesnake in such a way as to fill up the time embraced by the Sarmatian epoch of Europe. Absolute agreement as to the succession has not been reached, and the difficulty is increased by frequent uncertainty as to the exact position in a section in which specimens were collected. Personally I can base the classification as set out in the chart on pps. 10, 11 merely on the opinions of those American palaeontologists who have studied the subject most carefully. Stirton's papers of 1936 and 1939 in particular have been of the utmost value.

It will be seen that the most striking feature in which the correlation now presented differs from the ones previously in use consists in the greater interval of time allotted to the faunas from the Mascall and Pawnee Creek to the Blanco and Hagerman. There is little or no difference in the correlation of the faunas previous to this. At first sight it might be thought that the spacing out of the American faunas between the Barstow and Blanco is too great for the change of fauna involved. The alteration in the fauna is certainly less than what has taken place between the John Day and the Mascall. It cannot, however, be denied that the nearer we approach to recent times, the slower is the rate of change. For example, the difference between the faunas of Tatrot and Pinjor is slight compared to that between the faunas of Nagri and Dhok Pathan. The faunas of Romieu and Sansan seem remote from one another in comparison with those of Sebastopol and Taraklia. For this reason it seems to me that the faunas between the Barstow and the Blanco had hitherto been compressed into a smaller interval of time than one would expect.

Considering any one region the only causes which should produce a sharp distinction between the faunas of successive

Upper Miocene and Pliocene stages are : (1) The extinction of a large part of the previously existing fauna. (2) The arrival of migrants from another region. (3) The recrudescence of variation and specialization which in certain instances has occurred at relatively late epochs. The best instances of the third of these causes is to be found in the Bovidae in general and the Bovinae and Antilocaprinae in particular, also the Elephantoidea. For this reason the Elephants and the Bovines afford the best means of correlating the Pliocene and Pleistocene deposits of the Old World and the Antilocaprinae those of North America. Unfortunately *Elephas* did not reach America until an advanced stage of its development and the Bovines even later, while the Antilocaprinae vanished from Asia before the Pontian. The utility of these groups for American and European correlation is therefore much curtailed. At the same time the particular stage of development reached by the Elephants, Bovines, Caprines, and Ovibovines when they first reached America affords us some evidence for the time when this migration must have taken place.

The correlation with Europe of the faunas later than the Rattlesnake presents a difficult problem. The most important time marker for continental correlation seems to be *Equus*, of which the appearance in the Old and the New Worlds may be taken as simultaneous, on the assumption that the *Plesippus* stage did not migrate to Europe, so that *Equus* must have migrated as soon as it arose in America. This genus first appears in the Villafranchian of Europe, and in America in the Irvington (Stirton, 1939 *a*, p. 393) and Hay Springs (Matthew, 1902, p. 317) faunas. Since these American faunas contain *Elephas columbi*, which is at the same stage of development as *E. primigenius*, it is impossible that they should be as early as the Villafranchian, in which *E. planifrons* and *E. meridionalis* are the forms of Elephant represented. The Irvington fauna cannot, therefore, be earlier than Cromerian and then only on the assumption that *Elephas columbi* and *E. primigenius* originated in Asia and that the former reached America before the latter reached Western Europe.

The Hagerman Lake beds with *Plesippus* and no *Equus* must on this basis be earlier than the Villafranchian. According to Gazin (1936, p. 287) the Blanco appears not to be far removed from the Hagerman. All authorities agree that both are distinctly later than the Rattlesnake. Perhaps we may consider the Lower San Pedro (Benson) of Arizona with *Anancus bensonensis*, *Neohipparion*, *Merycodus*, and *Platygonus* as Plaisancian ; the Blanco and the Hagerman as Astian ; the Irvington and Hay

Springs as Cromerian. I can find no fauna in America which would correspond to the Villafranchian of Europe, the Pinjor of India, or the Nihowan of China, unless the Upper San Pedro (Curtis Flats) fauna may be assigned to this stage. According to Gidley's (1922 ; 1926) original lists, the Curtis fauna contains *Equus*, *Glyptotherium*, and *Stegomastodon arizonae*.

If the specimen recorded by Lewis (1937, p. 198) from Tatrot is really an *Equus* and not a *Plesippus*, some compromise may be necessary, but until the specimen has been described it is useless to speculate as to what form this might take.

The fauna of the American Falls, Idaho, the Melbourne beds of Florida, the McKittrick, and possibly those of Rancho La Brea and Big Bone Lick containing *Bison*, *Ovibos*, *Ursus*, and advanced *Equus* are certainly later than Cromerian, but it is hardly profitable to discuss their exact correlation in this paper.

The references to literature in the text are partly to the works listed by Simpson and Stirton in their papers of 1933 and 1936 respectively and partly to works which are not cited by these authors. Those coming under the latter category are listed below.

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The Lamellibranch Zones of the South Staffordshire Coalfield

By A. E. Trueman

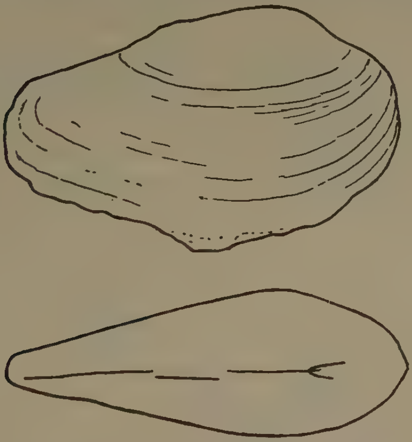
SCARCELY any information has been published regarding the palaeontological sequence in the Coal Measures of South Staffordshire. Some marine bands have been recorded (summarized in Whitehead, 1927, p. 31) and there are isolated records of non-marine lamellibranchs, including a number which were figured by Wheelton Hind (1894–6). Practically nothing is known, however, concerning the zonal succession of either the shells or plants in that area. Recently, through the kindness of Dr. C. J. Stubblefield, the writer has had an opportunity to study a small collection of shells obtained in South Staffordshire by the late H. W. Hughes and now in the Museum of the Geological Survey. The specimens have been collected from known horizons and have proved to be sufficient to enable the writer to fix zonal boundaries and thus to make some suggestions regarding the correlation of the marine horizons.

Professor L. J. Wills has also kindly afforded opportunities to examine some useful specimens in the Museum of the Geological Department at the University of Birmingham.

In many cases the shells may be referred to named species ; to other specimens, however, it appears to be unsatisfactory to attach definite specific names, especially where only single examples are available. It is in some cases uncertain whether these represent unusual variants of familiar species or whether they indicate the general character of the assemblages present in this coalfield. Certainly a number of the shells at present available from South Staffordshire show some peculiarity in features which makes a final determination impossible. In the notes which follow brief accounts are given of some of these specimens. In view of the wealth of illustrations of shells from the North Staffordshire coalfield provided by Wheelton Hind and others it is somewhat surprising to find so many shells in South Staffordshire which cannot be immediately compared with the specimens known from the neighbouring coalfield. Until more material is available, however, it is perhaps fruitless to speculate on the possible influence on these faunas of what may have been a somewhat different environment.

Notwithstanding these occasional difficulties in nomenclature there is no doubt as to the broad relationships of the forms represented and the recognition of the zonal positions indicated by the various faunas rarely affords any real difficulty.

For information regarding the sequence of the coals and ironstones in South Staffordshire the writer is indebted to Mr. T. H. Whitehead, and Dr. C. J. Stubblefield has made many useful suggestions in the course of the work. The sequence in various parts of the coalfield has been described in the Lichfield Memoir (1919) and in the Memoir on the southern part of the South Staffordshire coalfield (1927). Specimens described here include some from the Dudley area, of which an account will shortly be published by the Geological Survey.



Text-fig. 1.—*C.* cf. *communis* Davies and Trueman. Shallow Seam, Sneyd Pit, Essington. Birmingham University Collection. × 1·2 approx.

SUMMARY OF FAUNAL HORIZONS

Below the Deep Coal

Wheelton Hind (1895, p. 155) indicated that he had no record of any mollusca below the Pennystone horizon. Dr. Walcot Gibson (1908, p. 185) recorded *Carbonicola robusta* at a horizon 30 feet below the Deep Coal in Cannock and Rugeley. The writer has not been able to locate the specimens referred to, but in view of the fauna recorded at the next horizon it is not improbable that the shells are members of the group which is now known as *C. pseudorobusta* Trueman.

The Roof of the Bottom or Shallow Coal

Three specimens from this horizon are preserved in the Birmingham University collection. One of these, from the

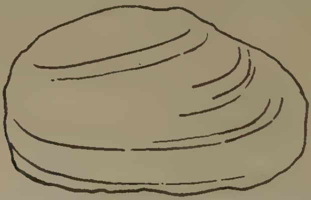
Shallow Seam of Sneyd Pit, Essington, shown in Text-fig. 1, is related to *C. communis* Davies and Trueman ; it is rather more pointed than the type of that species but it is not sufficiently heavy for *C. crista-galli* Wright. The other specimens are from Wood Farm, Bloxwich ; one of these is too poor to determine while the other may be recorded as *C.* cf. *rhomboidalis* Hind.

There is no doubt that this horizon falls within the Ovalis zone or right at the base of the Modiolaris zone.

Pennystone Ironstone

The upper part of the Pennystone Ironstone (and the lower part of the overlying New Mine Ironstone) contains marine fossils (Whitehead, 1927, p. 31).

A series of specimens of non-marine lamellibranchs from Doulton's Lower Clay Work, Netherton, are recorded as from the top of the Pennystone Measures. They may thus represent a horizon *above* the marine band.' The specimens include *C.* aff. *aquilina* (J. de C. Sowerby) ; some of these specimens are fairly typical but others show considerable variation. In several specimens there is a marked tilt of the growth lines and a tendency to develop an arched dorsal margin somewhat comparable with that in *C. phrygiana* Wright (Text-fig. 2) ; the shell, however, is not always so high as in that species, the anterior end is longer and there is a small distinct anterior lobe (Ze 4149, 4150). One specimen, although allied to *C. aquilina*, is much shorter and in shape resembles *C. regularis* Trueman (Ze 4155). A single specimen in the Birmingham University Collection from the Pennystone Ironstone of the Saltwells Clay Hole may be recorded as *C.* aff. *aquilina* (J. de C. Sowerby).

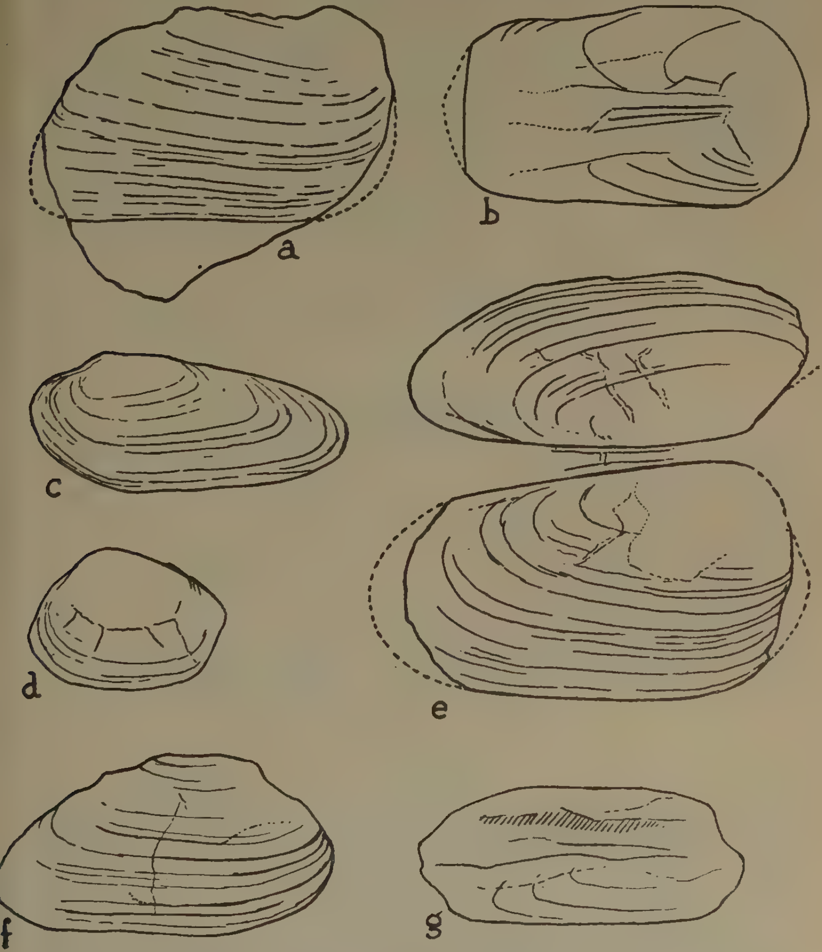


TEXT-FIG. 2.—*C. phrygiana* Wright. Top of Pennystone Measures, Doulton's Lower Clay Work, Netherton. Geol. Surv. Coll., Ze 4154. × 1·1 approx.

There is no doubt that this horizon cannot be lower than the Modiolaris zone.

Heathen Coal

Two very poor specimens from below the Lower Heathen Coal at Saltwells are in the Birmingham University Collection ; they are probably to be referred to *Naiadites* sp. A further

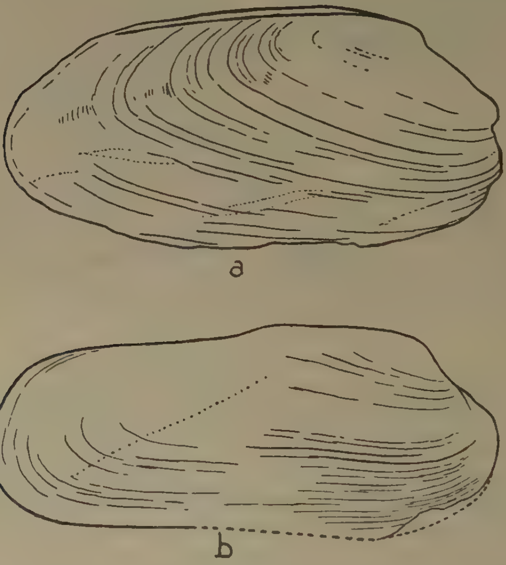


Text-fig. 3.—Shells from the Heathen Coal

a, *b*, *C.* sp., Geol. Surv. Coll., Ze 4209, × 1·3 approx. : *c*, *C. acutella* Wright, Geol. Surv. Coll., Ze 4181, × 1·5 approx. : *d*, *C. cf. regularis* Trueman, Geol. Surv. Coll., Ze 4212A, × 1·2 approx. : *e*, *C.* sp. nov. ?, Geol. Surv. Coll., Ze 4205, × 1·2 approx. : *f*, *g*, *C.* aff. *aquilina* (J. de C. Sow.), Geol. Surv. Coll., Ze 4208, × 1·4 approx. *c*, from Wednesbury Oak Colliery ; the remainder from Shaley Clod of Heathen, Morley Colliery.

specimen from below the Upper Heathen Coal at Doulton's Clay Pit, Saltwells, is almost indeterminable, but it probably represents a *Carbonicola.*

Much better material from the roof of the Heathen Coal occurs in the Survey collection from the Wednesbury Oak Quarry (Ze 4181–5) and from the Morley Colliery (Ze 4205–4214). Several of these specimens are illustrated in Text-fig. 3. The material from the first-named locality includes *C.* aff. *aquilina* (J. de C. Sowerby), *C. acutella* Wright, *C.* cf. *concinna* Wright, and *C.* cf. *regularis* Trueman. The specimens of the *aquilina* group in many cases show a much greater tilt of the growth lines than is usual in the species recorded. The shells from Morley Colliery (recorded from the Shaley Clod of the Heathen) include some forms similar to those just named, *C.* aff. *aquilina* and *C.* cf. *regularis* being both represented. There are, however, several unusual specimens of which one (Ze 4209) is possibly a new species; it may be a member of the *aquilina* group but it is a very high form (Text-fig. 3*a*). Another specimen



Text-fig. 4

a, C. aff. *aquilina* (J. de C. Sow.), Heathen Coal, Wednesbury Oak Colliery; Geol. Surv. Coll., Ze 4183B, × 4.
b, C. ? sp. nov. (Possibly *Anthracomya*), Shaley Clod of Heathen, Morley Colliery; Geol. Surv. Coll., Ze 4207, × 1·3.

(Ze 4207) is also an unusual type of shell unknown to the writer from any other coalfield ; it has a long and rather pointed anterior end and a peculiarly expanded posterior end in which it recalls species of *Anthracomya* (Text-fig. 4*b*).

Gubbin Ironstone

Wheelton Hind (1895, p. 155) gave the following list of species from this horizon : *Carbonicola acuta*, *C. aquilina*, *Anthracomya turgida*, *Naiadites modiolaris*, and *N. carinata*. The record of *A. turgida* is probably a misprint for *Carbonicola turgida* although Hind did not record this species from the Gubbin Ironstone in the Monograph. He nevertheless included it (p. 67) for the Grains Ironstone.

It is not possible to draw any useful conclusions from these records but they are not inconsistent with the view that the horizon falls within the Modiolaris zone.

Grains Ironstone

From this horizon Wheelton Hind has recorded *Carbonicola aquilina*, *C. nucularis*, *Anthracomya modiolaris*, *Naiadites modiolaris*, *N. carinata*, and *N. triangularis* (p. 155), while he also mentioned *C. turgida* (p. 67). Some of these specimens are figured in the Monograph. A shell referred to *C. aquilina* (and certainly a member of that group) is figured in plate ix, fig. 8, while a specimen referred to *Anthracomya modiolaris* from Dudley is illustrated in plate xvi, fig. 53 ; it is not quite a typical example of *A. modiolaris*, showing a much greater angulation of the lower posterior border. There is no doubt, however, that it is an *Anthracomya* indicative of the Modiolaris zone.

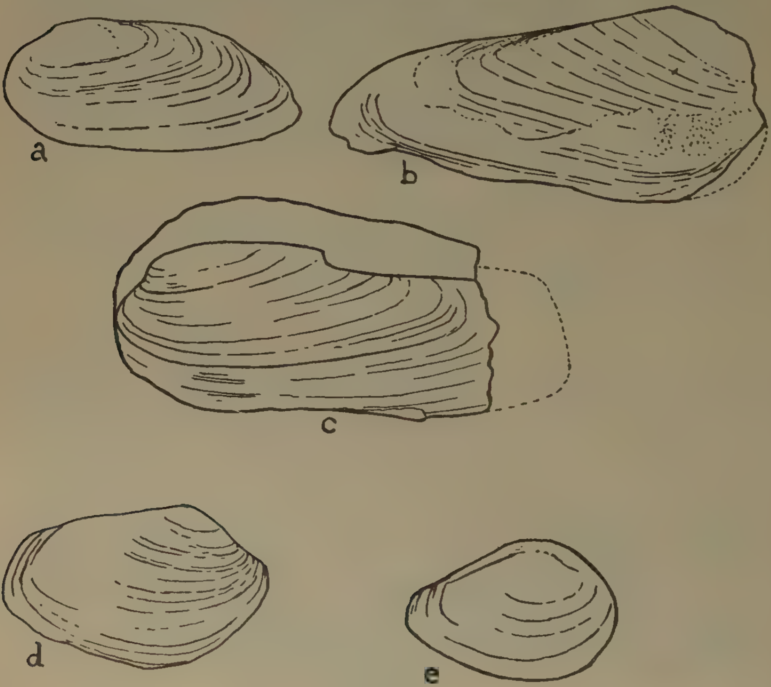
Between the Top and Bottom Thick Coal

From the Hob and Jack Horizon of Bilston, the Survey collection includes a number of specimens, all more or less related to the *C. aquilina* group ; one specimen (Ze 4199) may be regarded as a fairly typical *C. aquilina*. Several specimens (Ze 4200–4202*a*) are referred to *C.* cf. *concinna* Wright ; they have a rather more pointed posterior end and the posterior border is more sharply truncated, cutting the lower border at a somewhat more acute angle. A small shell is probably *C. lateralis* (Brown) while a larger specimen can only be recorded as *Carbonicola* sp. nov. ; it has a very short anterior end, pronounced inclination of the growth lines and (for a shell with these features) a curiously pointed posterior end (Text-fig. 5*b*).

Thick Coal

Wheelton Hind figured one specimen from this horizon at Tipton; he referred it to *C. aquilina*. It is a poor specimen and it is not possible to add anything to this identification.

In the collection of the Geological Survey are several specimens which may be recorded as *C. aquilina* from this horizon at the



TEXT-FIG. 5

a, *C.* cf. *concinna* Wright, Geol. Surv. Coll., Ze 4201, × 1·4 approx.; *b*, *C.*? sp. nov. Geol. Surv. Coll., Ze 4203, × 1·4 approx. Both specimens from Hob and Jack horizon, Bilston.

c, *C.* aff. *aquilina* (J. de C. Sow.), Birmingham Univ. Coll., × 1·2 approx. Measures above Thick Coal, Coombe Wood Colliery.

d, *C.* cf. *affinis* Davies and Trueman, Geol. Surv. Coll., Ze 4189, × 1·5 approx. Roof of Brooch Coal, Devil Pit, Great Bridge.

e, *C. similis* (Brown), Geol. Surv. Coll., Ze 4222, × 1·2 approx. Roof of Brooch Coal, loc. unrecorded.

Park Lane Colliery, Tipton. They are all crushed and fairly large forms. In some cases they are fairly typical examples of the species but they tend to have a more pointed posterior end than in the type of *C. aquilina*. Some of them thus resemble *C. atra* Trueman but the shell appears to be scarcely heavy enough for that species and the horizon is probably lower than that of the true *C. atra*. One specimen (Ze 4195) is recorded as *C.* cf. *aquilinoides* Tchern. In the Birmingham University Collection there are specimens from this horizon at the Coombes Wood Colliery. One of these is referred to *C. similis* (Brown); it is almost typical in shape but it shows slight radial markings. These markings, however, may not represent true radial ornamentation and they seem to be due to the crushing of an otherwise well-preserved shell. From the same locality is an elongated *Carbonicola* referred to *C.* cf. *acutella*. This shell is not quite so acute as typical examples of the species while, on the other hand, too pointed for *C. concinna*. It shows also a more definite tilt in the growth lines than is present in the holotypes of either species. A third specimen represents rather a larger shell with a pronounced tilt in the short anterior end. It can only be recorded as *C.* aff. *aquilina* s. lat. (Text-fig. 5*c*).

Ten-foot Ironstone Measures

From this horizon at Coseley, near Dudley, two specimens (Ze 4147 and 4149) show *Naiadites* aff. *triangularis* (J. de C. Sowerby) with associated *Spirorbis*.

Brooch Coal

Wheelton Hind's figures of specimens from the Brooch Coal illustrate specimens referred to *C. similis* and *C. aquilina* (pl. ix, figs. 3–4; pl. xi, figs. 6, 7, 9–13). Included in *C. similis* are some specimens which closely resemble Brown's species but many of the shells are more elongated than typical *C. similis*.

The same two species are represented in the material in the Survey collection, which includes several typical examples of *C. similis* (Ze 4222, Text-fig. 5*e*). In one or two cases these forms show a feeble radial ornamentation. One specimen (Ze 4186), recorded as *C.* ? *radiata* Wright, is similar in shape to Wright's species apart from a somewhat more pointed posterior end, and, while its radial ornamentation is not so striking as that developed on some Northumberland specimens (Trueman, 1933, p. 71) it is practically as distinct as that on the holotype.

A number of other specimens are recorded as *C.* cf. *acutella*; like some of the specimens in the roof of the Thick Coal they appear to combine to some extent the characteristics of *C. concinna* and *C. acutella*, but differ from both in having a much more pronounced inclination in their growth lines. Among the specimens from this horizon at the Wednesbury Oak Colliery are some which may be referred to *C.* cf. *affinis* or *C.* cf. *turgida* (Ze 4175, 4189; Text-fig. 5*d*); they are not so tumid as many members of those species and the shell is somewhat more smooth, but they are otherwise fairly typical.

The material from the roof of the Brooch Coal (especially that from the Devil Pit of Great Bridge) consists of extremely friable and crushed specimens in which *Carbonicola* greatly predominates. Occasional specimens of *Anthracomya* and *Naiadites* also occur. These are generally poorly preserved in the material available and complete examples are rare, but at least two species of *Anthracomya* are represented. One of these is recorded as *A.* aff. *adamsi* Salter; it is an expanded shell which clearly falls within that group (Ze 4186). Material from the roof of the Brooch Coal from an unrecorded locality includes a more elongate example of *Anthracomya* which is referred to *A.* cf. *oblonga* (Ze 4222).

Marine Band above the Brooch Coal

A marine horizon has been recorded by several observers above the Brooch Coal. At the Hamstead Colliery it occurred at 177 feet above the Thick Coal, while at the Sandwell Park Colliery it was 200 feet above the Thick Coal (*South Staffordshire Memoir*, p. 32). This horizon has been taken as the boundary between the Middle Coal Measures and the Etruria Marls.

Marine fossils have also been recorded at one locality below the Brooch Coal (between the Brooch Coal and the Herring Coal at Hamstead).

Other specimens from South Staffordshire in the Geological Survey collection confirm the general conclusions indicated above. Although they are not from known horizons, a number of shells from the Coal Measures of Dudley (15578–15587) include specimens referred to *C.* cf. *similis* (Brown), *C.* cf. *ovalis* (Martin), and *C.* ? *elliptica* Wright; they represent horizons from about the base of the Modiolaris Zone to the lower part of the Similis-Pulchra Zone. Some very fine specimens of *Naiadites quadrata* (J. de C. Sow.) are recorded from a factory, north-east of Oldbury, Dudley (15393–4, 15727) and from Portway Hall, Dudley (15396–7); the occurrence of so many examples of this unusual type of *Naiadites*, unaccompanied (in the collection at least) by examples of its more frequent associates, possibly indicates that at some horizons and in some areas, this "species" forms a distinctive group.

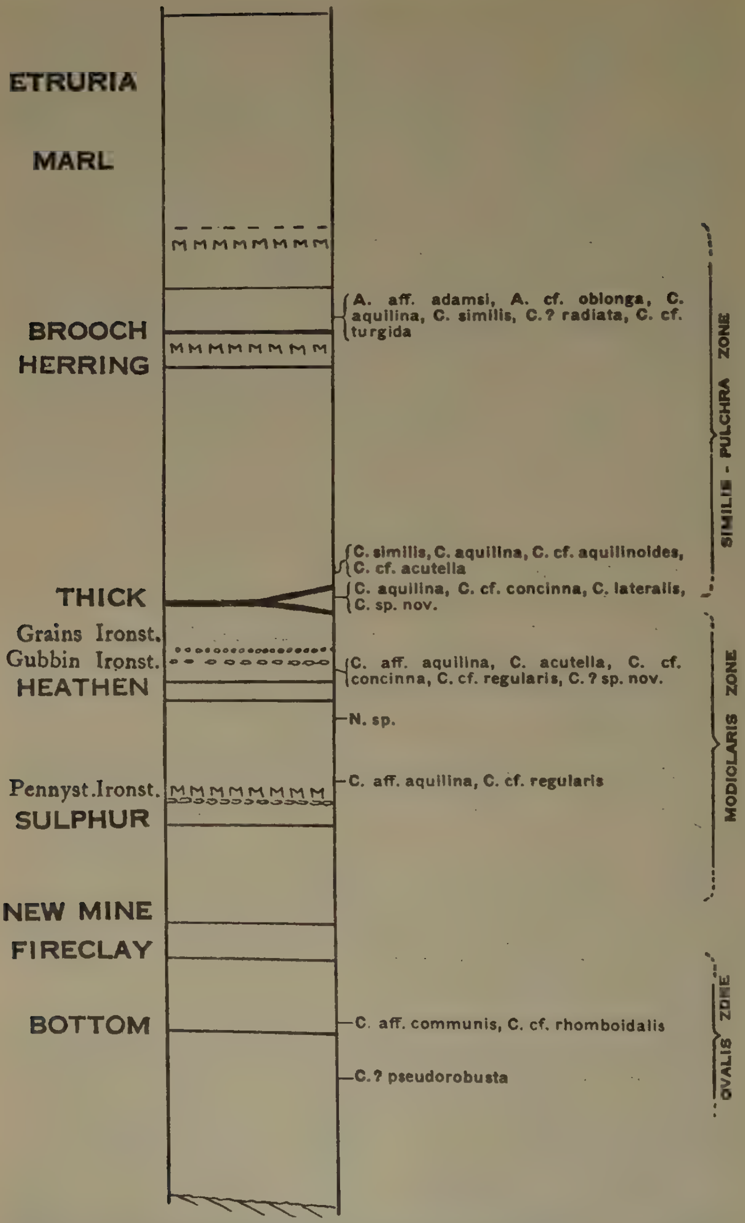
From Bilston, Staffs, two specimens indicate the Ovalis Zone, and are possibly from a horizon near the Bottom Coal; they are *C. pseudorobusta* Trueman (56619) and *C. crista-galli* Wright (56620). A number of small specimens from Aldridge, Staffs, represent the Modiolaris Zone; most of them are *Anthracomya* aff. *williamsoni* (Brown) and *A.* cf. *modiolaris* (J. de C. Sow.).

Reference may here be made to a very interesting specimen (PL 3464) from the roof of the Four-foot Coal of Walsall Wood Colliery (*Lichfield Memoir*, p. 95, footnote); this is incomplete, but can probably be referred to *Anthracomya* of the *A. adamsi* group; it is possibly very close to *A. hindi* Wright. Two apparently related specimens are represented by fragments on the same piece of ironstone. They appear to indicate a horizon in the Similis-Pulchra Zone, perhaps some distance above the base of the zone. The possible occurrence of a marine band some 22 feet below the Four-foot Coal is noteworthy and a fuller study of the faunal sequence in this area would no doubt be of great interest. Meantime, the exact position of these horizons in the sequence described is uncertain.

The Interpretation of the South Staffordshire Sequence

There is no doubt that the main series of coals in South Staffordshire fall within the Modiolaris and Similis-Pulchra zones. The abundance of *Carbonicola*, and especially of members of the *C. aquilina* group at most horizons, show that the majority of the coals lie within the upper Modiolaris zone and the lower part of the zone of Similis-Pulchra. The occurrence of lower horizons is indicated by such faunas as are available near the horizon of the Bottom or Shallow Coal, but *C. aquilina* has already appeared in strata associated with the Pennystone Ironstone, and the base of the Modiolaris zone must, therefore, lie at some distance below that horizon. In any event it appears that the lower part of the Modiolaris zone can only be thinly represented in South Staffordshire.

The records of *Anthracomya* in the coalfield show clearly that the Grains Ironstone must fall within the Modiolaris zone and that the Brooch Coal lies within the lower part of the Similis-Pulchra zone. The boundary between these two zones has been drawn provisionally near the horizon of the Thick Coal. This is supported by the record of *C. turgida* from either the Grains or the Gubbin Ironstone and by the abundance of Carbonicolas resembling *C. acutella* and *C. concinna* above the Thick Coal; although these shells are not always quite typical they are almost certainly related to these two species.


ETRURIA
MARL
BROOCH
HERRING
THICK
Grains Ironst.
Gubbin Ironst.
HEATHEN
Pennyst. Ironst.
SULPHUR
NEW MINE
FIRECLAY
BOTTOM
A. aff. adamsi, A. cf. oblonga, C. aquilina, C. similis, C.? radiata, C. cf. turgida
C. similis, C. aquilina, C. cf. aquilinoides, C. cf. acutella
C. aquilina, C. cf. concinna, C. lateralis, C. sp. nov.
C. aff. aquilina, C. acutella, C. cf. concinna, C. cf. regularis, C.? sp. nov.
N. sp.
C. aff. aquilina, C. cf. regularis
C. aff. communis, C. cf. rhomboidalis
C.? pseudorobusta
SIMILIS - PULCHRA ZONE
MODIOLARIS ZONE
OVALIS ZONE

TEXT-FIG. 6.—Generalized Section of the Coal Measures of South Staffordshire. Scale about 120 feet to 1 inch.

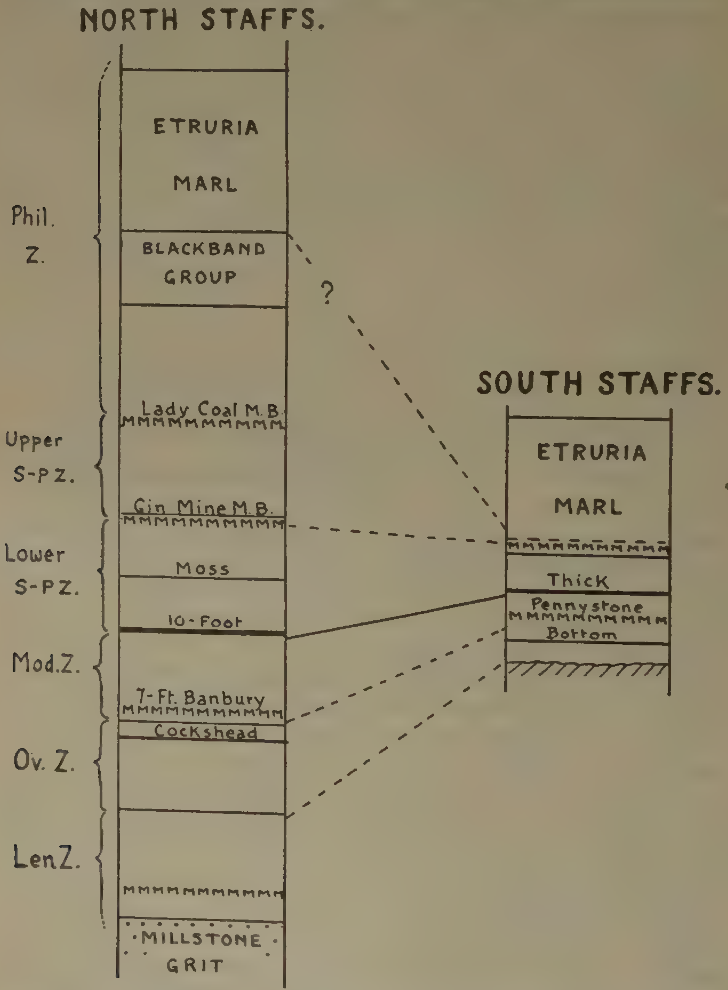
Although the Thick Coal is regarded as marking the base of the Similis-Pulchra zone it is by no means certain that the fauna in the roof of that coal represents the lowest fauna ordinarily to be found in the Similis-Pulchra zone. Owing to the coalescing southwards of a number of coal seams to form the Thick Coal it is probable that many horizons normally furnishing non-marine faunas in other coalfields are included within the thickness of coal. The fauna found immediately over this coal, however, is certainly from a horizon not far above the base of the zone. It may be remarked that in many coalfields a comparatively thick seam occurs at a corresponding horizon (e.g. the Nine-foot or Big Vein in South Wales, the Ten-foot in North Staffordshire, the Barnsley in Yorkshire, the Main in Cumberland, and the Musselband in Scotland). Although it is not certain that the formation of these seams was strictly contemporaneous it is possible that a widespread uniformity of conditions which led to the formation of thick coals in other areas was carried to a much further stage in the South Staffordshire coalfield.

In the faunas represented in the collections studied there is no evidence of any horizon higher than the middle of the Similis-Pulchra zone. The occurrence of *Anthracomya* aff. *adamsi* over the Brooch Coal is interesting, but clearly it indicates a horizon lower than that at which related shells are found in North Staffordshire, for the Anthracomyas which occur above the Brooch Coal are associated with abundant large Carbonicolas which are unknown above the Gin Mine horizon in North Staffordshire. The fauna of the Brooch Coal horizon more closely recalls those found near the Kent's Coals of Yorkshire, but it would be premature to assume their equivalence.

The zonal boundaries thus approximately fixed confirm the view that in passing southwards from North Staffordshire the lowest parts of the Coal Measures have almost completely disappeared. It is certain that most of the important coals of the Lenisulcata and Ovalis zones are unrepresented in South Staffordshire, except perhaps in the northern part of the coalfield (Barrow, 1917, p. 25).

While it is possible in this way to fix approximate zonal boundaries from the scanty faunas at present available, it will be observed that the evidence is quite inadequate for recording the presence of any of the subzones which have been named in Lancashire.

In connection with this zonal classification some reference may be made to the three marine horizons whose positions have been noted. The best known horizon, that in the Pennystone Measures, clearly falls within the Modiolaris zone and not higher than the middle of the zone. It is certain, therefore, that this horizon cannot be the equivalent of the Speedwell Marine Band (widely known as the Gin Mine Marine Band) as Mr. J. T. Stobbs and others have suggested (1905, p. 519).



Text-fig. 7.—Diagrammatic Sections of the Coal Measures of North and South Staffordshire. Approximate scale, 1,000 feet to 1 inch.

It has already been pointed out that the Pennystone horizon of Coalbrookdale, the presumed equivalent of the Pennystone in South Staffordshire, is succeeded by strata with *Carbonicola* and that it cannot be correlated with the Gin Mine horizon (Dix and Trueman, 1931, p. 202); Bisat (1930, p. 76) has reached a similar conclusion from a consideration of the goniatites. It is possible that the Pennystone may be equivalent to the marine band above the Seven-foot Banbury Coal in North Staffordshire (which is over 1,000 feet lower in the sequence than the Speedwell or Gin Mine Band). The Seven-foot Banbury marine horizon, however, appears to lie near or not far above the base of the Modiolaris Zone (Trueman, 1933, plate), and until more is known as to the precise position of the Pennystone in respect to the faunas with which it is associated this correlation can only be regarded as a suggestion. The presence of *C. aquilina* in strata associated with the Pennystone suggests a horizon well above the base of the Modiolaris Zone. The Pennystone marine band may thus occupy a position comparable with that of the Amman Marine Band of South Wales, which occurs near the middle of the Modiolaris Zone (Jones, 1935).

The marine horizon which has been recorded some distance above the Brooch Coal is much more likely to correspond to the Speedwell or Gin Mine Band, but as the faunas above that level in South Staffordshire are unknown it is again unsafe to assert the identity of these horizons.[1] It is suggestive, however, that another marine band occurs beneath the Brooch Coal in a position which, if the correspondence of the higher band with the Speedwell or Gin Mine is accepted, would indicate that the lower band may correspond with the marine horizon near the Moss Coal.

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[1] Since the above was written, Dr. C. J. Stubblefield has pointed out to the writer that a goniatite from this horizon may indicate correlation with a still higher horizon, the "Upper Cefn Coed Marine Band" (= the Cwmgorse Marine Band).

Fossils from the Fuller's Earth of the Weymouth Anticline

By W. J. Arkell

(PLATE I)

I. Occurrence

FULLER'S Earth was first recorded at the surface in the core of the Weymouth anticline by Damon (1860, p. 12). It was mapped by the Geological Survey in a semi-elliptical area south of Langton Herring, having a sea coast of about 1¼ miles on the West Fleet (1 inch map, sheet 341). The chief feature of interest is a lumachelle or oyster bed composed of a mass up to some 12 feet thick of the small oyster, *Ostrea hebridica* Forbes (= *O. sowerbyi* Morris and Lycett), the var. *elongata* Dutertre predominating (see Damon, 1860 and 1884, p. 12, fig. 3). The oyster was recorded by Damon and by Strahan (1898, p. 5, and sheet 341) as *O. acuminata* J. Sowerby, but that species belongs to a lower horizon, below the Fuller's Earth Rock. The Langton Herring oyster bed, which is seen also at Watton Cliff near Bridport, lies in the Upper Fuller's Earth, above the Fuller's Earth Rock, which does not come to the surface in the Weymouth anticline. The lowest beds exposed in the anticline, for a few feet below the oyster bed, are tough clays with mudstone nodules and abundant *Rhynchonella smithi* (Davidson) (see Arkell, 1933, p. 252). With the Rhynchonellids there weather out also abundant fragments of a typical Fuller's Earth belemnite, which I follow some French authors in calling *Belemnopsis bessina* (d'Orb.).

On the quarter-mile stretch of the West Fleet shore where these fossils occur, 1 mile west of Langton Herring church, I found in 1932 specimens of *Trigoniae* which I identified as *T. irregularis* Seebach and *T. elongata* J. de C. Sowerby, and large oysters different from any in the oyster bed and referred to *O. undosa* Phillips and *O. marshii* J. Sowerby. The two *Trigoniae* are known in the literature as characteristic of the Oxford Clay, but I could find with them none of the other Oxford Clay fossils which abound almost wherever that formation is exposed, *Gryphaea dilatata* J. Sowerby, *G. lituola* Lamarck, and ammonites of the genera *Kosmoceras*, *Quenstedtoceras* or *Cardioceras*. On the other hand there were fragments of large smooth-whorled ammonites, crushed flat and indeterminable, which seemed to agree better with *Proplanulites* than with any Oxford Clay genera.

The large oysters, too, are elsewhere commonest in the Upper Cornbrash, not the Oxford Clay. Consequently I suggested (1932, p. 44) that the source of the fossils might be Kellaways Clay. Since the *Trigoniae* are often perfectly preserved, free from matrix, and extremely fragile, it was evident that they could not have been transported far, and I postulated an outcrop of Kellaways Clay faulted down beneath the West Fleet off this part of the shore.

These suggestions were made in ignorance of a note by Colonel Cunnington on the same subject, published 7 years before (Cunnington, 1925). He had found at this spot the same two species of *Trigoniae* and Dr. L. R. Cox had identified them for him with the same names as I gave them, and had concluded that they came out of Oxford Clay. The following additional fossils were also recorded by Cox : *Nucula cottaldini*, *Astarte multiformis*, *Parallelodon montanayensis*, *Anisocardia* sp. *Perisphinctes* sp., all suggesting the Oxford Clay so far as they went. Cunnington suggested that they may have been washed down from the nearest outcrop of Oxford Clay 2 miles up the Fleet, possibly during the flood caused by the tide breaking through the Chesil Bank 100 years ago. Two reasons led me to reject this idea when I suggested the faulting : namely, that the fossils are too fragile and well preserved to have travelled, and that the same species are found in no other part of the Fleet. The strictly limited distribution was also noticed by Colonel Cunnington.

During 1939 I have obtained from the same place as before numerous crushed fragments of the smooth-whorled ammonites. Many retain signs of ribbing, which make it clear that they are not *Proplanulites*, nor any other Oxford Clay or Kellaways genus. The conviction steadily grew that the ammonites, oysters, and *Trigoniae* were weathering out of the low slipped bank of the Fleet and from the solid clay foreshore.

Accordingly in July, 1939, I dug into the bank opposite the stretch of beach where the fossils are numerous and at a point less overgrown than most, where the base of the oyster bed is exposed in a small cliff about 4 feet high. A section of tough dark grey clay was laid bare to a depth of 3 feet below the oyster bed and was excavated. In the clay, *in situ* just above high water mark, were found specimens of both the familiar *Trigoniae*, the commonest of the large oysters (*O. undosa*), and the characteristic crushed ammonites, associated with *Belemnopsis bessina* (d'Orb.), *Rhynchonella smithi* (Davidson), and var. *crassa* Muir-Wood, the Zeillerid *Rugitela powerstockensis* Muir-Wood, and numerous fragile lamellibranchs, of which the commonest are *Modiola anatina* Wm. Smith (= *M. gibbosa* J. Sow.), a small *Astarte*, a *Cucullaea* or *Grammatodon*, *Camptonectes*, *Thracia*, *Nucula*,[1] and *Isocyprina* ?

Dr. H. M. Muir-Wood, who has kindly identified the brachiopods, states that *Rugitela powerstockensis* is known elsewhere only in the Watton Cliff Brachiopod Beds at Eype and in the Beaminster and Sherborne districts, and *Rhynchonella smithi* var. *crassa* is also characteristic of those beds.

It appears, therefore, that the lowest fossil-bearing Fuller's Earth at Langton Herring is near the horizon of the Watton Cliff Brachiopod Beds (see Welch, 1933 ; Muir-Wood, 1936, pp. 20–3).

II. The Trigoniae (Plate I)

Lycett in his monograph on British fossil *Trigoniae* (1872–9) mentioned only one species from the Fuller's Earth, the miniature *T. witchelli* Lycett, from near Stroud.

The costate species from Langton Herring (pl. i, figs. 1, 2, 7) recorded previously as *T. elongata* J. de C. Sowerby (1823, vol. v, p. 39, pl. ccccxxxi), cannot be distinguished specifically from the Oxford Clay species of that name. Compared with a syntype in the British Museum (no. 43131) from Radipole Backwater, Weymouth, and abundant topotypes, it differs only in having the area and escutcheon rather more finely ornamented, and the outer carina slightly narrower and more finely crenulated ; and the whole shell and especially the hinge region is rather lighter in build. In the left valve the anterior part of the area bears 5 to 7 radial costellae, compared with 4 and occasionally 5 in the Oxford Clay species. A new varietal name might be justified if these characters were all constant for the Fuller's Earth, but some perfectly preserved specimens, with the valves united, from the Watton Cliff Brachiopod Beds of Beaminster and Toller Porcorum (Welch, 1933), collected by me about 1932 in Dr. Welch's company, show ornamentation of the area and carinae just as coarse as in Weymouth Oxford Clay *elongata* (pl. i, fig. 3). These North Dorset Fuller's Earth specimens are also less " elongate " (broader) than the Langton Herring or Weymouth *elongata*, a fact which led to my recording them (1939, p. 2) as *T. castor* d'Orbigny (see Thevenin, 1912, p. 146, pl. xxvii, fig. 19, and Bigot, 1893, p. 27, pl. ii, figs. 6, 7 ;

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[1] A large *Nucula* with full prominent umbones, found also in the Upper Fuller's Earth at Cliff End, Burton Bradstock, associated with *N. waltoni* Morris and Lycett.

pl. iv, fig. 7). But the left valve of *T. castor*, figured by Cossmann (1914, p. 23, pl. viii, figs. 7–9), has the area much more coarsely ornamented and the groove anterior to the marginal carina narrower. The Langton Herring shells seem identical with *T. elongata* var. *lata* Lycett, from the Scarborough Upper Cornbrash, and one of Lycett's figures of var. *lata* shows five costellae on the area.

Costate *Trigoniae*, probably belonging to the same species, but too badly preserved for specific determination, have been found in the Lower Fuller's Earth of West Bay cliffs (Brit. Mus. Nat. Hist., nos. L. 7571, L. 9591).

The clavellate *Trigoniae* from Langton Herring (pl. 1, figs. 4–6) recorded by Dr. Cox and myself as *T. irregularis* Seebach are likewise at first sight very similar to the Weymouth type material of that species. Seebach's name (1864, pp. 117–8) was founded on *T. clavellata* Damon (1860, pl. ii, fig. 3), also from the Oxford Clay of Radipole Backwater, Weymouth. Lycett (1872, p. 39) rightly remarked that Damon's figure represents an extreme example of the irregularity in the arrangement of the tubercles. Among more than a dozen double-valved topotypes there is not one with such irregular tuberculation as shown in Damon's figure; and the only specimen from the Damon Collection acquired by the British Museum (no. L. 6773), since marked as the type, has normal tuberculation as shown in Lycett's pl. v, fig. 1.

T. elongata and *T. irregularis* are not now to be found at any of the Oxford Clay sections near Weymouth, the old Radipole Backwater exposure having been obliterated many years ago. Nor is it known from what zone they came. The possibility has been considered that J. de C. Sowerby and Damon and all subsequent authors might erroneously have accepted Fuller's Earth *Trigoniae* from the Fleet Backwater for Oxford Clay fossils from Radipole Backwater. Sowerby stated that the type of *T. elongata* had been sent him by a correspondent in Wiltshire, Miss Benett, and Damon (1884, p. 33) rather cryptically added lithological notes about these two species, the only ones to have such notes in a list of 78 species from the Weymouth Oxford Clay. Lycett might have copied these authors, and Mansel-Pleydell (1879, pp. 117, 127) certainly copied Lycett (changing "Backwater" to "Breakwater"). But there is a strong piece of circumstantial evidence against this hypothesis: all the Langton Herring *Trigoniae* are single valves, whereas nearly all those labelled Oxford Clay, Radipole or Weymouth, have the two valves united.

The most telling evidence, however, derives from the morphology of the clavellate *Trigoniae*. On closer examination the perfect specimens from Langton Herring now available cannot be united with *T. irregularis* Seebach, of which they lack the produced, acute, somewhat twisted posterior end ; and their carinae are distinctly less tuberculated than in the Oxford Clay species. They agree specifically rather with *T. scarburgensis* Lycett (1872, p. 31, pl. iv, figs. 1–4) hitherto known only from the Upper Cornbrash of Yorkshire, Lincolnshire, and some other counties, and from the Lower Callovian of Normandy (Bigot, 1893, p. 59). The particular kind of undulating irregularity in the rows of tubercles, with the intercalation of an extra half row, is characteristic of *T. scarburgensis*, and the details of the area, escutcheon, and carinae are the same.

I have collected fragmentary *T. scarburgensis* also in the Upper Fuller's Earth clay at Cliff End, Burton Bradstock, 30–50 feet below the Boueti Bed (recorded as *Trigonia* sp. in Arkell, 1933, p. 253). It occurs also in the Brachiopod Beds of Watton Cliff (Buckman Coll., Brit. Mus. no. L. 10005) but so far has not been recorded inland. There is another specimen in the British Museum (L. 9592) labelled " Fuller's Earth, West Bay ".

Thus two more Upper Cornbrash lamellibranchs, *T. elongata* var. *lata* Lycett and *T. scarburgensis* Lycett, are added to the Fuller's Earth list, besides the large oysters already mentioned. The number of species common to the Fuller's Earth Rock and Cornbrash has been stressed recently (Arkell, 1939, p. 2).

III. The Ammonites

Ammonites from the Upper Fuller's Earth being almost unknown, it is of interest to find them abundant at Langton Herring. The commonest are fragmentary specimens of large *Procerites*. The preservation is peculiar. Nearly always the shell is crushed flat, but the thick test is perfectly preserved. The resulting fragments are from 40 to 80 mm. in diameter and 4 to 8 mm. thick, like pieces of tile or potsherds, with the ornamentation of the ammonite on both sides. About 35 such pieces have been collected, mainly from the beach, but including several dug out of the cliff. In addition there are 2 pieces of uncrushed septate whorl showing a high, rather compressed whorl-section with evenly-rounded rather narrow venter : whorl-height 100 mm., thickness 55 mm. ; and height about 85 mm. and thickness 50 mm. (both from the beach). Finally there are 3 fragments of crushed small ammonites or inner whorls (whorl height 20–22 mm.) which will be discussed later (these, too, are from the beach); and a small *Hecticoceras* dug out of the cliff, resembling *H. haugi* Popovici-Hatzeg but with simpler sutures.

Of the large *Procerites* of *Proplanulites*-like aspect, some fragments agree well with *P. procerus* (Seebach) as figured from Balin by Neumayr (1871, p. 39, pl. x, fig. 1, pl. xi, fig. 1) and the whorl-section is identical. Most of the fragments, however, have fainter primary ribbing, and some of the largest are entirely smooth except for faint secondaries. Comparison with the type (Geol. Survey Mus. no. 47200) suggests that specific identification could probably be made with *Procerites tmetolobus* Buckman (1923, vol. iv, pl. CDXVI) from the Zigzag Bed of Burton Bradstock, Dorset. Other fragments, with smoother ribbing and primaries wider apart, seem identical with *Procerites fullonicus* (Buckman, sp., 1922, vol. iv, pl. CCCII*), known only from the holotype (Geol. Surv. Mus. no. 26985) from the *Ostrea knorrii* beds, Combe Hay, near Bath (see Richardson, 1910, p. 426). Another possible identification is *P. quercinus* (Terquem and Jourdy, 1869, p. 44, pl. i, figs. 10–13, fig. 10 half natural size), from the upper *Ostrea knorrii* beds of the Moselle.

Very similar forms from the Zigzag Bed of Broad Windsor, Dorset, were assigned by Buckman to *Zigzagiceras*, namely his *Z. subprocerum* and *Z. clausiprocerum* (Buckman, 1925–6, vol. vi, pls. DCXXIV, DXCV), and have been figured from the " Arbustigerus Zone " of the Maconnais by Lissajous (1923, pp. 83–5, pls. x, xi), that is, from beds which he equated with the " Quercinus Zone " of the Moselle and the Fuller's Earth, Fuller's Earth Rock, and Stonesfield Slate of England. These species answer to Buckman's definition of *Procerites*—" compressed forms of *zigzag* origin in which *zigzag* ornament is soon lost," rather than to his own definition of his genus *Zigzagiceras*—" massive forms of *zigzag* origin in which the *zigzag* stage persists for some time " (Buckman, 1921, vol. iii, p. 31).

Large *Procerites* of essentially similar type, however, are by no means confined to the Zigzag Bed at the base of the Fuller's Earth, but range up in the Stonesfield Slate and the Hampen Marly Beds. *Procerites gracilis* (J. Buckman) is a well-known fossil of the Stonesfield Slate of Oxfordshire and the Cotswolds (see S. S. Buckman, 1920, vol. iii, pl. CXCII). Some specimens grow to over a foot in diameter, with smooth outer whorls (Oxford University Museum). *P. imitator* (S. Buckman sp., 1922, vol. iv, pl. CCCI), a less compressed species, is based on a specimen from the black pseudo-oolite called " Birds-Nest Rock " near the base of the Hampen Marly Beds of the Great Oolite, at Fritwell cutting (see Arkell, Richardson, and Pringle, 1933, p. 345). It would be necessary to find specimens more complete than those now available from Langton Herring before it could be decided whether the earlier or the later species provide the nearest comparison. From what is now known of the long range of species of other large Perisphinctoid stocks in the Corallian and Portland Beds, it is possible that the same species range up from the Zigzag Bed through the entire Fuller's Earth.

Of the three fragments of small ammonites, two are inner whorls of *Procerites*, comparable with *P. procerus* Seebach sp. (1864, p. 155, pl. x, fig. 2), as originally figured from the *Ostrea knorrii* beds of Eime near Hanover, and more especially (allowing for flattening) a specimen figured by Buckman (1892, p. 452, pl. xiii, fig. 1) from Broad Windsor as " intermediate between *zigzag* and *procerum* ". A badly preserved nucleus of this style was found in the Fuller's Earth of Sapperton Tunnel, Gloucestershire (Geol. Survey Mus. no. 69931). Owing to uncertainty in interpreting Seebach's drawing, it is perhaps best to comprise such forms in *Procerites rotundatus* (J. Roemer sp., 1911, p. 44, pls. v, viii, ix, xii), so well figured from the Aspidoides Beds of Lechstedt near Hildesheim and recognized in the Arbustigerus Zone of the Maconnais by Lissajous (1923, p. 78, pl. xii, fig. 2).

The third small fragment is indeterminable but is probably part of a coarse-ribbed Grossouvrid, or perhaps a *Wagnericeras*.

After the above notes were completed, I applied to the British Museum for loan of an ammonite from Langton Herring identified by Dr. Spath as " *Phylloceras* and perhaps a new species " (in Cunnington, 1928, p. 216). It arrived labelled " *Procerites* ", and it is in fact a more complete specimen of one of the species collected by me, being 283 mm. in diameter with half a whorl missing ; but it is likewise completely flattened and not identifiable specifically (Brit. Mus. no. C. 28502).

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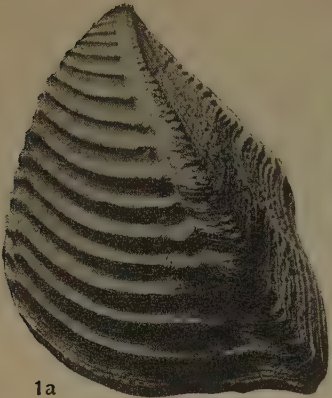

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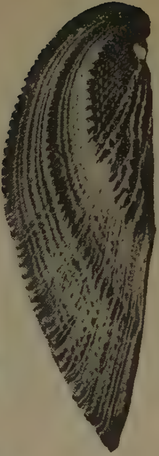

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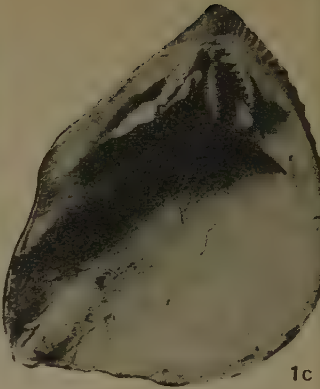

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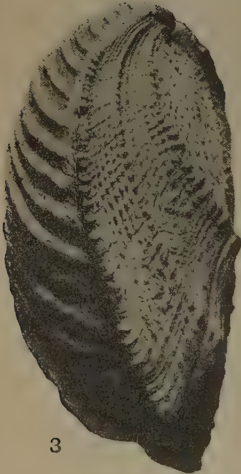

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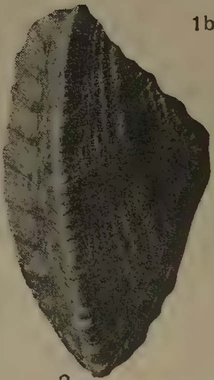

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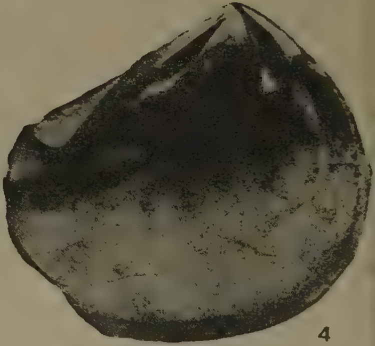

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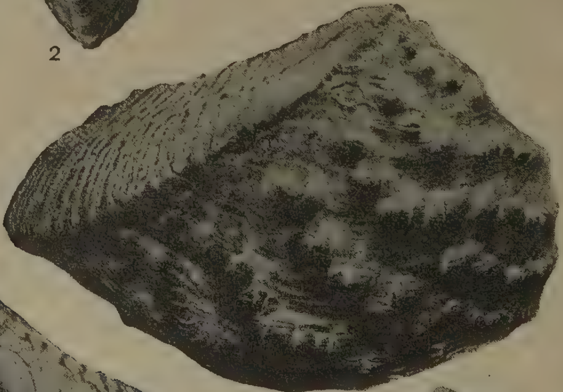

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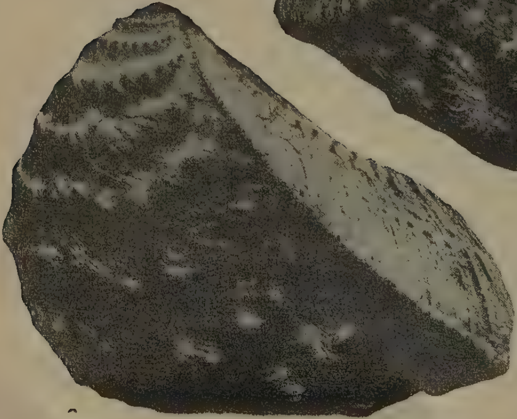

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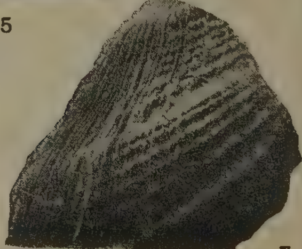

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EXPLANATION OF PLATE I

Figs. 1*a*, 1*b*, 1*c*.—*Trigonia elongata* J. de C. Sowerby, var. *lata* Lycett. Three views of a left valve. Fuller's Earth, Langton Herring, Dorset.

Fig. 2.—Part of a larger left valve. Same locality.

Fig. 3.—Left valve of a more coarsely ornamented specimen with both valves preserved. Watton Cliff Brachiopod Beds, near Beaminster, Dorset.

Fig. 7.—Part of a large right valve of the same species. Fuller's Earth, Langton Herring, Dorset.

Figs. 4, 5, 6.—*Trigonia scarburgensis* Lycett. The specimen in Fig. 4 lacks part of the posterior end, that in Fig. 5 lacks the umbo. Fuller's Earth, Langton Herring, Dorset.

All photos natural size by the author, from specimens collected by him.

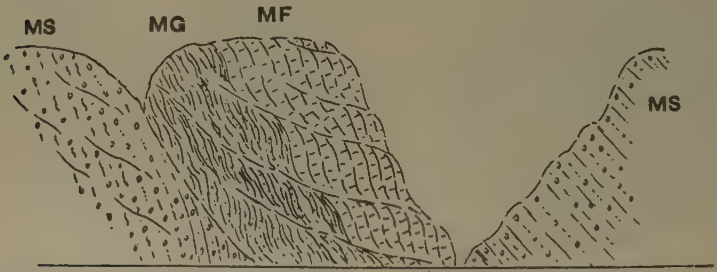
Studies in the Mona Complex

By E. Greenly

I. The Fydlyn Beds of Bull Bay, a correction

MY paper on The succession and metamorphism of the Mona Complex [1] contains (p. 339) an error of some importance, which I have long desired to correct.

It is not the case that the Gwna Beds of Bull Bay fail to reach the coast. Some years after the publication of that paper, I was able to examine the cliff from below by means of a boat. This revealed that the Fydlyn Beds are succeeded (or rather underlain) on the south by about 30 feet of green Gwna phyllite-and-grit mélange (Text-fig. 1) [E. 14935, 14949]. This is followed on the south by about 160 feet of rock whose characters are intermediate between the Church Bay Tuffs and Skerries Grits, beyond which are typical Skerries Grits.



Text-fig. 1. Cliff section at Bull Bay. (Height about 60 feet.) MF = Fydlyn Beds ; MG = Gwana Beds ; MS = Church Bay Tuffs.

On the southern side of the Gwna Beds there is certainly a rupture, though perhaps not very great. But the junction of Gwna mélange and Fydlyn Beds is not a rupture : it is a zone of passage by alternation. Thus, the section is not merely of local, but of stratigraphical importance, for it adds another piece of evidence that the Gwna Beds and Fydlyn Beds are knit together by a belt of gradual alternation (*Geology of Anglesey*, p. 161, and *Quart. Journ. Geol. Soc.*, 1923, p. 337).

True, the passage is rapid, but hardly more so than at Fydlyn and Mynachdy. The belt runs down the cliff steeply, and then out along a reef at the cliff's foot. It is curved sigmoidally, and repeatedly driven southward by small thrusts at low angles.

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[1] *Quart. Journ. Geol. Soc.*, lxxix, 1923, 334–351.

The remainder of the published account does not call for serious modification. What we have here is a ruptured major isoclinal infold of the inverted northern succession, taking in Gwna Beds, pitching eastward, and just bringing in Fydlyn Beds at the meridian of the present coastline. We may legitimately suppose that the thinness of the Gwna Beds can be explained, in part, by their having been reduced in thickness by the local waste whereof the pebbles in the Skerries Group are evidence, but perhaps even more by ruptures due to the tendency to subsidence on the pitch, which cut out some of them, as well as the *typical* Church Bay Tuffs, leaving only the part which has characters akin to the Skerries Grits, and in general reducing the width of the infold.

II. THE AGE OF THE GNEISSES

In the same paper, seven new pieces of evidence were adduced that the crystallization and foliation of the Gneisses is older than the deposition of the Bedded Succession. Here is another, of a somewhat different kind.

In the country about Holland Arms, gneisses, mainly basic, are seen very close to (sometimes only a few yards from) hornblende-schists and mica-schists of the Penmynydd Zone, and it might be supposed that the latter are dynamic reconstructions of the acid and basic types of gneiss. But, in the first place, the basic gneisses are heavily mylonized, whereas the rocks of the Penmynydd Zone are remarkably uninjured. In the second place, as we approach the junction, there is no sign whatever that the Penmynydd-Zone foliation is superimposed upon that of the gneiss. Indeed, the mica-schist of the Penmynydd Zone is known (*Geology of Anglesey*, pp. 122–3) to be, in this district, a modification of *rhyolitic* rocks, and at the crag shown in Text-fig. 10 (*Geology of Anglesey*), rhyolite positively intervenes between mica-schist and gneiss, so that the Penmynydd Zone metamorphism is developing in a direction *away from* the gneiss.

Further, it may be asked whether the basic gneisses can be merely the deep-seated cores of the intrusions from which came the sills that are now the hornblende-schists of the Penmynydd Zone? Well, in the first place, the gneisses are highly heterogeneous, and quite unlike the simple diorites which occur as cores in the hornblende-schists of the Penmynydd Zone, while they even include a 25 ft. band of acid albitic gneiss. In the second place, their distribution is completely independent of the hornblende-schists. In the third place, were they the sources of those schists, the sills must have arrived at the positions where we now see them before the basic-gneiss magma had consolidated. Let us put the thesis that the said magma was the source of the sills. Now, in the same paper (*Quart. Journ. Geol. Soc.*, pp. 343–8) it was shown that all the complicated structures of the basic gneiss—its banding, its folding, and its three generations of pegmatite—are subsequent to the consolidation of that basic magma. Those structures must therefore be subsequent to the intrusion of the sills. And as the sills would consolidate more rapidly than their deep-seated source, the gneissic structures must be subsequent even to the consolidation of the sills. How then, and when, were those structures induced? Certainly not by the movements which induced the Penmynydd anamorphism, for the strike, very steady in the Penmynydd Zone, is very variable in the Gneisses, the two strikes diverging at the junction at an angle of no less than 62°. So the structures of the Gneisses are conspicuously independent of those of the Penmynydd Zone. But the sills are now hornblende-schist. To maintain this thesis, therefore, we are driven to interpose all the complicated processes which induced the gneissic structures either before or just after the Penmynydd anamorphism, which is a *reductio ad absurdum.*

Accordingly, the basic gneisses cannot be the sources of any of the basic rocks of the Bedded Succession.

But if they existed, structures and all complete, before the Bedded Succession came into existence, then their relations to the adjacent hornblende-schists present no difficulty. It is probable that these gneisses, heavily mylonized as they are, and appearing as they all do, along the western margin of the Aethwy Region, are shattered katamorphic nips like those of Mynachdy, brought in on infolds of the (primary) Newborough slide. This is also confirmed by the evidence derived from the Ordovician grit of Berw.[1]

In a recent book, however, entitled *A Hand through Time* (p. 477) I have written as follows: " But are the Gneisses an Ancient Floor? In *Q.J.G.S.*, 1923, I adduce seven new pieces of evidence that the crystallization and foliation of the Gneisses are older than the deposition of the Bedded Succession, and No. 7 is very strong, indeed it seems to me conclusive. Nevertheless, their proximity, in the Middle Region, to the Coedana Granite is, I cannot but feel, a suspicious circumstance. Does that granite, in spite of the difference of felspars, in spite of the persistent contrasts between gneiss and hornfels, belong to the Gneisses after all? Let us suppose that it does belong to them, and then consider the consequences. There is one place only, Mynydd Bodafon, where it seems to invade the Bedded Succession. If it do so, and if it belong to the Gneisses, they cannot be an Ancient Floor. But does it invade the Succession? I correlated (tentatively it is true) the hornfels with the Skerries Group. Is that correlation sound? Can that hornfels, also, be a portion of an Ancient Floor? Some of the pebbles which are unequivocally from such a Floor are less metamorphosed than the hornfels. Others are full of tourmaline, and so is the hornfels. It appears to graduate into the Bodafon quartzite, but is that really the Gwna quartzite? may it be something older?" It is strangely isolated and is not accompanied either by the persistent limestone with graphitic schist of the western Gwna facies, or by the spilitic lavas with ashy rose-limestones of the eastern Gwna facies. "The perplexities are great. I am still inclined to think that those presented by separation of Coedana Granite from Gneisses are the lesser of the two. Yet, in such a formation as the Mona Complex, we must be always prepared for surprises." Nevertheless, the evidence adduced in the present article adds greatly to the weight of the cumulative evidence, already heavy, in favour of regarding the visible Gneisses as parts of an Ancient Floor.

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[1] Greenly and Boswell, *Quart. Journ. Geol. Soc.*, lxxxviii, 1932, 297–311.

The Dolerite Plugs of Tieveragh and Tievebulliagh near Cushendall, Co. Antrim, with a Note on Buchite

By S. I. TOMKEIEFF, King's College, University of Durham, Newcastle-on-Tyne

I. INTRODUCTION

AMONG the numerous volcanic necks of County Antrim, two—Tieveragh and Tievebulliagh in the neighbourhood of Cushendall—are particularly interesting, the one because it has metamorphosed the country rock into buchite, and the other because of the existence on its scree of a rock of problematic origin. In connection with the buchite of Tieveragh a general note on the name buchite, its origin and its application, has been included at the end of this paper. The paper itself makes no claims to do more than open up the study of these rocks.

II. THE GRANULARITY OF THE ROCKS

The granularity of the rocks described in this paper is given in terms of average linear intercepts (Tables I and II). The average linear intercept (l) of a given mineral is calculated by dividing the total traverse on the Shand stage by the number of grains measured. The average linear intercept of the whole rock (L), mesostasis excepted, can be calculated by means of the following formula :—

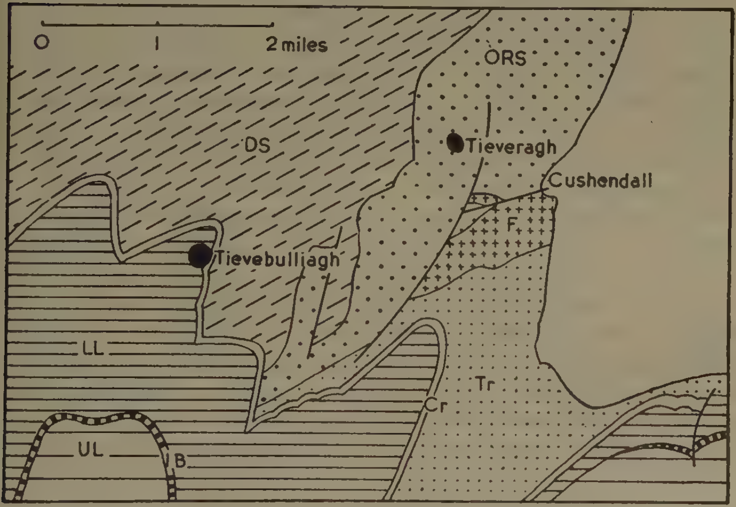
$$\mathrm{L} = \frac{l_1 p_1 + l_2 p_2 + \ldots + l_m p_m}{p_1 + p_2 + \ldots + p_m}$$

in which p is the volume percentage of a given mineral in the mode.

The average linear intercept is used here as the index of granularity. According to this index I have drawn the line separating basalt from dolerite at $L = 0 \cdot 100$ mm., and that separating dolerite from gabbro at $L = 0 \cdot 400$ mm. This excludes phenocrysts, but the rocks described in this paper are not porphyritic.

III. TIEVERAGH

Tieveragh is a picturesque conical hill half a mile N.W. of Cushendall. It was recognized by McHenry (8, p. 19) to be a volcanic neck infilled with dolerite. It is slightly elliptical in cross-section, with an average diameter of 600 feet. It breaks through tufaceous sandstone and conglomerate of Old Red Sandstone age. The centre of the plug is composed of olivine-dolerite similar to other Irish dolerites of Tertiary age. The exposures are not good and in the samples studied the olivine is completely serpentinized, although labradorite and poikilophitic purplish augite are quite fresh. Iron-ore is usually moulded on plagioclase and the mesostasis consists of chlorite and fibrous zeolite. The dolerite is coarse right up to the margin of the plug. Two or three feet from the contact a small exposure of dolerite displays a remarkably coarse rock very rich in olivine. According to its granularity (Table I, No. 2) this rock should be classed as gabbro. The olivine is fresh and it occurs in the form of large irregular crystals. As measured on the Fedorov stage its optic axial angle varies from 90° to 86°, and therefore its composition varies from Fo_{87} Fa_{13} to Fo_{77} Fa_{23} (Mol. per cent). It is only slightly zoned. The plagioclase is a zoned labradorite. The ophitic pyroxene with $2V = 56°$ and $\gamma : c = 41°$, appears to



TEXT-FIG. 1.—DS = Dalradian Schists; ORS = Old Red Sandstone and conglomerate; F = Felstone-porphyry; Tr = Trias (conglomerate, sandstone and marl); Cr = Chalk and Greensand; LL = Lower Plateau Lavas; IB = Interbasaltic lateritic zone; UL = Upper Plateau Lavas; Black shading = intrusive dolerite; minor faults and dykes are omitted.

be a normal augite. A rather abundant mesostasis consists of radial and tufted chloritic aggregates.

Towards the margin of the plug this olivine-rich rock passes rapidly into an almost olivine-free fine-grained dolerite. The feldspar of the marginal dolerite is also labradorite but strongly zoned to oligoclase. The greatest change, however, is shown by the pyroxene which occurs in the form of idiomorphic and hypidiomorphic elongated prisms with salite lamination and herring-bone structure. According to its optical properties ($2V = 48°, \gamma : c = 33°$) it shows an approach towards pigeonite. This is probably due to the disappearance of the magnesian olivine in the rock.

The actual contact of dolerite with the country rock is not exposed, but on the N.W. side of the hill, rocks within a few inches of the contact can be collected. In order to obtain samples of the contact rocks a small trench has been dug by the combined efforts of the students of Bristol University and King's College, Newcastle-on-Tyne, to whom my gratitude is due. But as a continuous section across the contact aureole is impossible without digging a very long trench, the unaltered sandstone had to be collected from a small excavation some 500 feet to the north of the hill. The sediments in this excavation are flaggy coarse-grained greyish sandstones with bands of conglomerate. Under the microscope the sandstone is seen to be composed mainly of angular and subangular fragments of an altered felsitic rock, and of comparatively few fragments of altered andesitic or basaltic rock, quartz with mosaic structure and wavy extinction, and highly altered alkali feldspar. These fragments are cemented by microfibrous silica and ferruginous material The specific gravity of the sandstone is 2·512 and its porosity is 15 per cent.

On the N.W. side of the hill a shell of baked and fused sandstone surrounding the dolerite plug is well exposed. At first glance this rock looks like a fine-grained compact basalt. It is a dark grey compact rock with a dull lustre, a hackly fracture, and its specific gravity is 2·577. Under the microscope this rock shows a sandstone palimpsest in spite of alteration and vitrification of its constituents. The cement of the sandstone is completely replaced by glass (refractive index of about 1·50). The glass is full of minute grains and crystallites of iron-ore, pyroxene, sericite, and feldspar, but cordierite has not been observed. The quartz shows resorption but it preserves its mosaic structure and wavy extinction. The feldspar is highly sericitized. The fragments of igneous rocks are partly vitrified but the feldspar laths in them are much clearer than in the fragments of the fresh and unaltered sandstone. They are usually surrounded by dusty iron ore.

Within a few feet of the contact this rock passes into a dark pitchstone-like rock with platy jointing and a sub-conchoidal fracture. Its specific gravity is 2·423. Under the microscope it is seen to be composed mainly of brownish glass of refractive index of about 1·48. Of the original minerals of the sandstone only partly resorbed relic grains of quartz are present The mosaic structure and the wavy extinction can still be observed. These grains are surrounded by a very narrow zone composed of minute colourless needles and plates of the same refractive index as the quartz. Similar needles and plates are also found in the cracks of quartz grains and they may perhaps represent cristobalite retransformed into quartz The new minerals which occur as small crystals in the glass are as follows : (1) cordierite, rectangular and hexagonal sections, occasionally showing sector twinning ; (2) clinopyroxene in clusters of granular crystals ; (3) basic labradorite laths, fresh, often with terminal faces ; (4) orthopyroxene, yellowish-brown, slightly pleochroic, extinction usually straight in longitudinal sections and at 45° in basal sections ; (5) a mineral not yet identified—it is found in the form of skeletal, thread-like, and nebular aggregates of minute rectangular prisms with an extinction angle from 35° to 45°—it may be a clinopyroxene. The rock shows a high grade metamorphism and may be called a vitric cordierite-buchite.

A couple of inches from the contact the vitric cordierite-buchite passes into a compact greyish rock shot with green and of a dull lustre. Its specific gravity is 2·620. Of the original minerals of the sandstone it contains only quartz which is similar to that found in the previously described rock. The amount of glass (refractive index slightly below 1·50) is small, but it provides the groundmass for the minerals of the new formation. Feldspar (probably sanidine), in the form of short prismatic crystals, is extremely abundant and clusters of pyroxene grains are common Cordierite is also present together with chlorite, iron-ore, and calcite. This rock may be called a lithic buchite. Slow cooling and the presence of volatiles were probably responsible for the high development of crystalline minerals in this rock. Its contact with dolerite is sharp. Very frequently a feldspar-rich zone is developed along the contact and a similar feldspar rich material forms minute veinlets injected in the dolerite. This suggests an alkali-enriched mobilized sediment.

The contact dolerite is a moderately coarse rock It is highly contaminated with sedimentary material which appears as spots of buchite up to 0·5 cm. in diameter. The contaminated dolerite forms a zone of two or three inches thick. Under the microscope the contaminated dolerite appears to be similar to the marginal dolerite (Table I, No. 3), being composed of labradorite, prismatic pyroxene, iron ore and a little serpentinized olivine, but it has numerous patches of buchitic material (Table I, Nos. 4 and 5). These patches consist of an indefinite felsitic groundmass in which are dispersed numerous microlites of sanidine and plagioclase. The felsitic groundmass appears to be composed of plagioclase (andesine ?) and a small amount of elongated microlites of a dark mineral which could not be identified with certainty but appears to be a variety of pyroxene. Water-clear sanidine is in the form of rectangular or rhombic prisms with hollow ends. These give sections of elongated rectangles and rhombs with forked terminations or of hollow squares. Very often the prongs of the fork pass into branching feathery tufts. Sanidine crystals often enclose small plagioclase laths. The plagioclase crystals are fresh and also show forked and tufted terminations. In composition the plagioclase corresponds to labradorite zoned to oligoclase. Glass is completely absent. These patches appear to represent sedimentary material caught up by the magma and completely recrystallized. No doubt a certain amount of transfusion took place between the magma and the sediments.

A number of feldspar crystals from the buchite and the buchitic patches in the dolerite were measured on the Fedorov stage. Unfortunately the determination of the optic axial angle of these crystals could not be carried out satisfactorily because of their minute size and because of a curious and as yet unexplained optical effect which occurred when the actual position of the axis was determined in the diagonal position on the stage. Instead of giving a flashing shadow as is the case with other minerals, the feldspar showed a shadow extending over a large angle. This may be due to the presence of cryptoperthite. In spite of the difficulty it was found that the majority of the feldspar crystals are uniaxial or with a small optic axial angle (not more than 20°) and negative and are thus probably sanidine, while some positive crystals may be albite. Nearly all crystals are zoned with a clearly defined outer narrow rim showing a higher optic axial angle than the central part (maximum $2V = 45°$) and this may be anorthoclase. The refractive index as measured by immersion in liquids varies from 1·52 to 1·53 in different sections.

IV. TIEVEBULLIAGH

Tievebulliagh is situated at the edge of the plateau-lava scarp, 2½ miles west of Cushendall. Hitherto its true nature has eluded geologists. There is no mention of its being a plug in the Geological Survey Memoir (8) and on the map (Sheet 14) it is not differentiated from the surrounding plateau-lavas. Its intrusive nature is admirably revealed in the scarp section. The dolerite plug is seen there to cut right through the horizontal Lower Plateau-lavas. The visible diameter of the plug is about 320 yards. The southern junction of the plug is obscured by screes but it appears to be vertical at the col separating the plug from the lavas. The northern junction appears to be dipping inwards but this may be due to the curvature of the plug margin. The base of the exposed portion of the plug is covered by screes and its downward prolongation into the underlying Chalk is not seen.

The plug is traversed by a set of parallel joints hading S.W. at an angle of about 10°. At the N.E. margin of the plug the joints curve down and meet the junction line at right angles. The curvature of columnar joints in plugs is a well-known phenomenon, a good example being the dolerite plug at Ballygalley Head (21) and, although the jointing of the Tievebulliagh plug is not columnar, it may represent an analogous case.

(*a*) *The lavas surrounding the plug*

These lavas are of the usual type of the Lower Plateau-lavas of Antrim. According to their granularity they vary from olivine-dolerite to olivine-basalt (Table II, Nos. 4 and 5). They are composed of partly serpentinized olivine, labradorite, purplish-brown ophitic augite, iron ore, chlorite, and a small amount of interstitial zeolite. Vesicles are usually filled with chlorite and zeolite.

Along the junction with the plug the lavas are greatly affected by thermal metamorphism. Signs of alteration are noticeable at 25 feet from the contact. The metamorphism becomes progressively more intense as one approaches the contact, and at about one yard from the contact the rock is fused to glass (refr. index 1·545) with only a few ill-defined remnants of the original minerals. The specific gravity of the glassy rock is 2·835. Generally speaking the metamorphism of these lavas is expressed in the serpentinization of olivine, albitization of plagioclase, transformation of ophitic crystals of augite into a fine-grained aggregate of augite crystals, and the development of secondary chlorite and epidote in the vesicles. Drawn-out vesicles and the general fluidal nature of the contact rock suggest a high degree of fusion.

(*b*) *The olivine-dolerite of the plug*

The plug itself consists of a bluish-grey fresh olivine-dolerite. The olivine is zonal and sometimes ophitically encloses plagioclase laths. Three grains of olivine measured on the Fedorov stage gave the following optic axial angles (the corresponding mol. percentage of fayalite is given in brackets) :

Centre ·	92 (8)	90 (13)	88·5 (17)
Margin ·	86·5 (23)	84·5 (27)	83 (30)

The labradorite laths are fresh and only slightly zoned. The poikilophitic purplish augite is fresh. The iron-ore is often moulded on plagioclase laths. There is a definite decrease of the granularity of the rock towards the contact, where the dolerite passes into basalt (Table II, Nos. 1, 2, and 3). The contact rock is extremely fine-grained and altered.

(*c*) *The spotted porcellanite*

The screes surrounding the plug are composed of fragments of dolerite and basalt, but among these are fragments of a curious mottled rock. This is an extremely compact and hard greyish rock varying from a leucocratic (sp. gr. 3·041) to a melanocratic (sp. gr. 3·232) type The leucocratic type has dark oval patches, lenticles, and bands on a light background. In the melanocratic type these relations are reversed. The rock is very hard, nearly as hard as quartz. It shows a conchoidal fracture and on the whole it has an appearance of a baked shale or porcellanite, except that ordinary porcellanite has a much lower specific gravity.

Under the microscope the rock shows a typical maculose texture with dark opaque portions sharply separated from the light portions which are made up of a felt-like aggregate of minute colourless acicular crystals. A chemical test, made on isolated grains of the dark material, indicated the abundance of alumina and iron oxides. This suggests an iron-alumina-spinel, pleonast or hercynite.

Among the grains of the opaque mineral, minute prisms and grains of a yellowish-brown birefringent mineral can be seen in some sections of the porcellanite. This mineral appears to have a moderate refringence, although higher than that of the leucocratic portion. The extinction is oblique. The precise nature of this mineral could not be ascertained.

Isolated fragments of the leucocratic portion were subjected to a rough chemical test which gave $SiO_2 = 36$, and $R_2O_3 =$ 61 per cent, and only traces of CaO and MgO. This suggests an alumina silicate, perhaps sillimanite or mullite. The refractive index of the fibrous aggregate is close to 1·59 but some larger crystals gave 1·63. The birefringence is moderate and the extinction is straight. The refractive index of 1·59 is much too low for sillimanite, although fibrolite, a variety of sillimanite, is reported to have an index of 1·63.

As far as I know no rock composed of spinel, sillimanite, and mullite has ever been described Thomas described aluminous xenoliths composed of spinel, sillimanite (mullite) corundum and cordierite (17, 18) and also xenoliths composed of spinel, sapphire, and anorthite (19), and de Lapparent described a rock composed of diaspore and magnetite (23). All these rocks are apparently metamorphosed bauxitic clays and ferruginous bauxites. My own tentative suggestion is that the mottled rock of Tievebulliagh is a metamorphosed aluminous pisolitic iron-ore or a ferruginous bauxitic clay. The presence of such a rock in the scree of Tievebulliagh is not easy to account for; glacial transport is precluded by the angular nature of the fragments and their location on the scree. Another explanation is necessarily hypothetical. Pisolitic iron-ore interbedded with bauxitic clay and laterite is found in the major interbasaltic zone in Antrim. The nearest outcrop of these rocks is 1½ miles south of Tievebulliagh and, if extended, it would be found not more than 100 feet, and probably much less, above the present summit of Tievebulliagh (1,346 feet). It is possible that the fragments of mottled porcellanite represent an aluminous pisolitic iron-ore formerly in place above the present level of the hill and thermally metamorphosed by the intrusive doleritic magma. The main bulk of this rock would since have been removed by denudation, with only a small number of fragments preserved in the scree. The removal of this rock has probably been facilitated by the Neolithic stone-axe workers, as a large number of prehistoric implements made of this rock have been found in Ireland and elsewhere. It would be interesting to trace the distribution of these axes, because as far as I know this rock has not been found in any other locality.

V. A NOTE ON BUCHITE AND SOME OTHER THERMAL-METAMORPHIC ROCKS

Strange as it may seem, no one, apparently, knows the origin and derivation of the name "buchite". My own effort, supplemented by those of Dr. K. F. Chudoba, of the University of Bonn, has been completely unsuccessful. It has no place in Zirkel's *Lehrbuch* of 1866 (1), and there is no reference to the name in literature prior to 1873. The first mention of buchite is made by Möhl in 1873 (3), and there is reason to believe that he is responsible for the name, which he probably coined in honour of Leopold von Buch. Mohl defines buchite as fused sandstone (geglühtes Sandstein) and gives a good description of it, illustrated by an excellent colour plate. He describes in minute detail corroded quartz grains and glass with newly-formed minerals. In the previous year (1872) Zirkel (2) had noted a water-clear mineral occurring in rectangular and hexagonal forms in the glass of a rock which he called fused sandstone, but which was later called buchite. He had suggested that the mineral was nepheline and Möhl accepted this suggestion both in the 1873 paper and in his subsequent paper on buchite (4), but Hussak (6) and Prohaska (7) proved the mineral to be cordierite, and Zirkel (9) accepted their conclusions.

Among the numerous references to and descriptions of buchite the following works may be mentioned: Lemberg (5) who gave a number of chemical analyses of buchite, Morosevicz (10) who provided the experimental physico-chemical basis for the understanding of cordierite-bearing rocks, Teall (11) who gave a summary of Morosevicz's work, Bücking (12), Harker (13), Cornu (15), Flett (16), and Schoklitsch (22). All these authors refer to buchite as vitrified sandstone, but in 1908 Flett (14) extended its connotation by including vitrified phyllite, and in 1922 Thomas (17) by including vitrified aluminous clay. This raises the question of nomenclature and classification of thermal-metamorphic rocks of the argillaceous-arenaceous series. Jugovics (20) would restrict the name buchite to arenaceous rocks, applying to rocks of argillaceous composition the old name, basalt-jasper. The term basalt-jasper is, however, both self-contradictory and not used in this country. The old name porcellanite is definitely preferable as applied to thermally metamorphosed clays, shales, and similar rocks. Samosite, corundolite, and the mottled porcellanite of Tievebulliagh may perhaps be also included in this group as representing metamorphosed bauxites, laterites, and analogous rocks.

This classification is based on composition alone, but another scheme of classification based on texture is quite feasible. In this case the name buchite would be reserved for vitreous or semi-vitreous rocks, porcellanite would apply to finely crystalline rocks, and hornfels to coarsely crystalline rocks.

In conclusion, I have to thank Dr. C. E. Tilley for kindly reading through the manuscript and for helpful suggestions and criticism.

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TABLE I

Olivine-dolerite, Tieveragh

Modal Analyses in Weight Per Cent

	(1)	(2)	(3)	(4)	(5)
Olivine . .	6·10	36·50	1·41	1·40	1·17
Feldspar . .	60·77	16·73	44·59	34·75	23·70
Pyroxene . . .	19·87	29·60	25·45	27·66	24·25
Iron ore . . .	1·79	1·77	4·10	5·88	6·33
Chloritic mesostasis .	11·47	15·40	24·45	2·51	4·95
Buchitic mesostasis .	—	—	—	27·80	39·60
Spec. Grav. . .	2·716	2·864	2·772	2·768	2·667

Granularity (in mm.)

	(1)	(2)	(3)	(4)	(5)
Olivine .	0·254	0·747	0·240	0·128	0·153
Feldspar . .	0·182	0·260	0·188	0·114	0·098
Pyroxene . .	0·598	0·728	0·414	0·196	0·169
Iron ore .	0·049	0·059	0·085	0·070	0·079
L	0·269	0·552	0·244	0·142	0·127

1. Central part of the plug.
2. Olivine-rich variety, 2–3 feet from the contact.
3. Marginal dolerite.
4. About 6 inches from the contact.
5. At the contact

TABLE II

Olivine-dolerite and Olivine-basalt, Tievebulliagh

Modal Analyses in Weight Per Cent

	(1)	(2)	(3)	(4)	(5)
Olivine . . .	14·95	19·35	17·20	17·50	15·05
Feldspar . . .	51·70	51·95	50·60	39·00	35·45
Pyroxene . . .	27·55	20·60	26·60	25·00	33·50
Iron ore . . .	5·75	7·60	3·95	5·55	8·75
Mesostasis .	0·05	0·50	1·65	12·45	7·25
Spec. Grav. . .	2·938	2·921	2·946	2·765	2·880

Granularity (in mm.)

	(1)	(2)	(3)	(4)	(5)
Olivine . .	0·133	0·193	0·071	0·327	0·119
Feldspar . .	0·106	0·086	0·065	0·084	0·030
Pyroxene . .	0·432	0·331	0·119	0·424	0·138
Iron ore . . .	0·045	0·044	0·023	0·033	0·019
L	0·190	0·150	0·076	0·224	0·081

1. Central part of the plug.
2. 20 feet from the contact.
3. 6 feet from the contact.
4. Central part of a lava-flow. North of the plug.
5. Marginal part of a lava-flow. South of the plug.

New Scottish Material of Eusthenopteron

By T. Stanley Westoll, Marischal College, Aberdeen

(PLATE II)

I. INTRODUCTION

THE existence of the Crossopterygian fish *Eusthenopteron* in the Old Red Sandstone of the Moray Firth area has been recorded recently by the writer (Westoll, 1937) Since that time new material has been found in the collections of the Royal Scottish Museum , the specimens comprise a " parietal " shield and other remains from Boghole, and an imperfect " fronto-ethmoid " shield, of which the provenance is unknown. Dr. A C. Stephen, of the Royal Scottish Museum, has been most kind in allowing the writer to study this and other comparative material.

The present paper includes a short comparative description of these remains, together with notes on certain points of importance in the nomenclature of the bones

II. DESCRIPTION OF MATERIAL

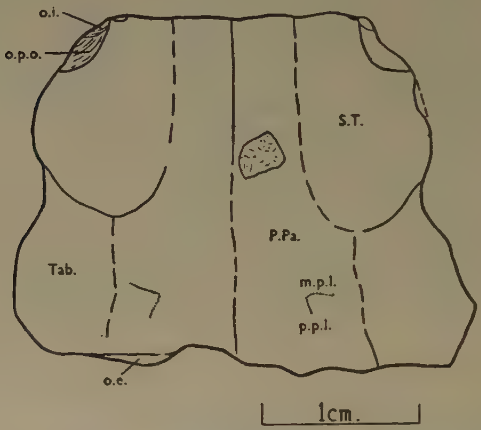
Eusthenopteron traquairi, Westoll, 1937.

The holotype of this species was collected from the yellow and red sandstones of Boghole, on the Muckle Burn, near Nairn. There is good reason to believe that the stratigraphical horizon is near the junction of the *Asterolepis* and *Bothriolepis* zones. The holotype consists of a " fronto-ethmoid " shield, lacking most of the bone and preserved mainly as a sharp internal mould of the dermal elements The supraorbitals and the posterior margins of the " frontals " were absent. Among the new material there has been recognized an excellent " parietal " shield, besides a poorly preserved mandibular ramus and other fragments which are not described here.

The " parietal shield " (1903, 63, 95) is preserved in the same coarse, gritty, yellow and red sandstone as the holotype, and shows the actual bone-surface. The following measurements indicate the size of the shield :—

	mm.
Length in mid-line	22
Maximum Breadth across " Supratemporals " . . .	29
Maximum Breadth across " Intertemporals " . .	25·5
Maximum Breadth across anterior margin	2[illegible]·5
Breadth across the exposed external faces of the bones. anterior margin	17

It is extremely difficult to distinguish sutures, but careful examination of the specimen immersed in various fluids, using very brilliant illumination, has enabled Text-fig. 1 to be drawn. The shapes and relations of the bones will be clear from this. The main point deserving comment is the clearly-marked overlap for the postorbital on each " intertemporal ". Immediately mesial to this there is a slight indication of the overlap of the " dermosphenotic " on the anterior margins of the " intertemporal ".



Text-fig. 1.—*Eusthenopteron traquairi* Westoll. " Parietal " shield. The exact course of some of the sutures is uncertain. Royal Scottish Museum, 1903, 63, 95.

Explanation of lettering for all figures. (Based on the revised nomenclature.)

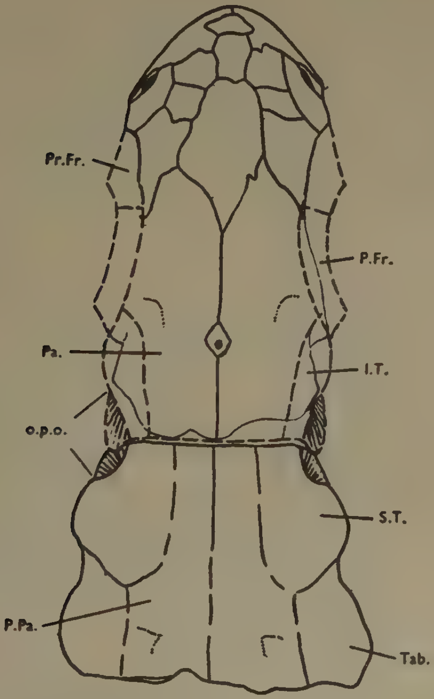
I.T., " Dermosphenotic " (Intertemporal) ; " Na," " Nasal " (part of fronto-nasal series) ; Pa, " Frontal " (Parietal) ; P.Fr., " Supraorbital " (Post-frontal) ; P.Pa., " Parietal " (Post-parietal) ; Pr.Fr., " Posterior Antorbital " (Pre-frontal) ; Pt.Ros., Post-rostral ; S.T., " Intertemporal " (Supratemporal) ; Tab. " Supratemporal " (Tabular) ; a.p.l., anterior pit-line ; m.p.l., middle pit-line ; p.p.l., posterior pit-line ; o.e., overlap-area for extrascapular ; o.i., overlap-area for " dermosphenotic " ; o.par., overlap-area for " parietal " ; o.p.o., overlap-area for postorbital ; o.p.f., overlap-area for " supraorbital ".

The " intertemporals " and " supratemporals " contain very numerous ramifying tubules of the latero-sensory canals—a condition common in *Eusthenopteron* (cf. Jarvik, 1937, Fig. 6). The middle pit-lines are rather poorly developed on the " parietals " and there is little sign of their existence on the

" supratemporals ". The short posterior pit-lines are clearly shown.

The ornament of the dermal bones consists of rounded tubercles, rarely separate, and usually coalescing by their bases to form short rugae without any very regular arrangement.

The " parietal " shield is from an individual somewhat smaller than the holotype. An attempt is made (Text-fig. 2) to combine the two specimens by magnifying them to comparable size. It is now apparent that the comparison previously made between the holotype and a skull-roof of *E. foordi* Whiteaves (Westoll, 1937, Fig. 2) was not quite correct ; the full length of the " fronto-ethmoid " shield of the holotype of *E. traquairi* is almost



TEXT-FIG. 2.—*Eusthenopteron traquairi* Westoll. Combined restoration of the holotype and the new " parietal " shield. The outline of the holotype is indicated by thin lines in the posterior part of the " fronto-ethmoid " shield ; that region and the bones of the orbital margin are restored in heavy dotted lines. Total length about 9 cm.

certainly preserved, though its posterior margin is damaged, and the former assumption that the lengths of the skull in species of *Eusthenopteron* should be compared from the front of the snout to the pineal foramen is now known to be wrong. The holotype should therefore be more readily comparable with normal material of *E. foordi* because it was necessary to use an extremely slender specimen of that species for comparison in the previous paper.

In Text-fig. 2, the shape of the posterior part of the holotype is conjecturally restored. The proportion, length of "fronto-ethmoid" shield : length of "parietal shield" is about 1·85, which agrees with the ratio for *E. foordi* (1·85), and is quite different from that found for *Tristichopterus alatus* (1·4). This new information fully confirms the reference of the species to *Eusthenopteron*.

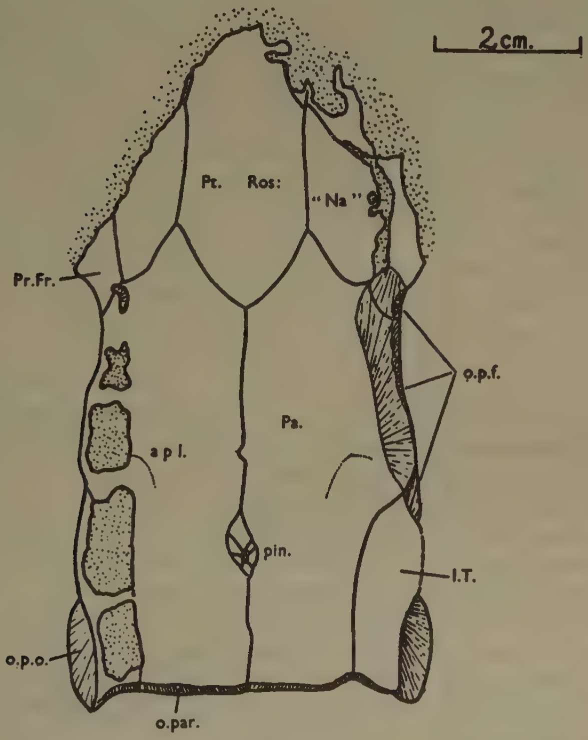
Eusthenopteron cf *traquairi*.

A large imperfect "fronto-ethmoid" shield in the Royal Scottish Museum is also referable to *Eusthenopteron*. It is preserved as an external mould, lacking the most anterior parts. The matrix gives the only clue to its provenance; it seems certain that the specimen comes from the upper part of the Old Red Sandstone of the Elgin district, as the Sandstone can be matched in the strata exposed there—e.g. in the small quarry between Rosebrae and the main Elgin-Nairn road. There is thus good foundation for the belief that the specimen is from higher in the Old Red Sandstone than the holotype of *E. traquairi*. The matrix consists of a fairly fine-grained bedded yellow sandstone with galls and pellets of green clay.

The shield as preserved is 89 mm. long, and was originally about 105 mm. long in the natural state of curvature. The mould is fairly sharp, but there are certain patches in which the bone seems to have been destroyed before fossilization, so that the matrix now stands up above the general level. It is difficult to account for these conditions. Sutures are quite clear, even in the circum-pineal plates, and the overlap areas at the lateral and posterior margins of the shield are well preserved. The supraorbitals are not shown, though there may be remains of this bone on the left side in the region where the bone-surface is damaged

The "frontals" are extremely well shown. The lateral area, overlapped by the supraorbital, is very wide, and is grooved so that the radiating structure of the bone is clearly seen. A slight dorsal flange of the "frontal", once overlapping the mesial edge of the supraorbital, has been broken off before fossilization.

It can be shown from the grooves on the overlap areas that the centre of radiation is situated just below the lateral part of the anterior pit-line, which is fully shown on the left side. This centre is considerably in advance of the pineal foramen (about 11 mm. in front). The pineal foramen is situated between the "frontals" at about their posterior third, and is surrounded by a series of six circum-pineal elements, which make up a very elongated, roughly rhombic, area. These plates comprise a large anterior and a small posterior unpaired element, and two pairs of small lateral bones. The pineal foramen itself is almost round, a little less than 1 mm. in diameter.



TEXT-FIG. 3.—*Eusthenopteron* cf. *traquairi* Westoll. Fronto-ethmoid shield, locality unknown. Royal Scottish Museum.

The " dermosphenotics " are present in place, but the external surface of the left " dermosphenotic " has been removed before the formation of the external mould, and only the lateral overlap area is visible. This area, for the overlap of the postorbital, is slightly grooved along the radiating structure of the bone, and is a little shorter and wider than that in *E. säve-söderberghi* (Jarvik, 1937, Figs. 6 and 7). The mould is not well enough preserved to show the details of the dorsal overlap of the " dermosphenotic " on to the postorbital in front of this region, but there is an exceptionally broad flange on the " frontal " and prefrontal (= " posterior antorbital "—see Westoll, 1937, p. 519), for the overlap of the supraorbital. Posteriorly the " frontals " and " dermosphenotics " show a narrow flange, almost exactly like that (figured by Jarvik, 1937, Text-figs. 6 and 7), which was overlapped in *E. säve-söderberghi* by the " parietal " and " intertemporal ".

Between the anterior ends of the " frontals " is a single rather long post-rostral, incomplete anteriorly. Laterally this is flanked by a long pair of " nasals ", also incompletely preserved. The prefrontals are very fragmentary, and that of the right side is separated from the " nasals " by one of the areas of bone-destruction. In general, therefore, the structure of the skull is like that of the holotype of *E. säve-söderberghi* Jarvik, and differs from the Boghole *E. traquairi* only in the different number of " post-rostrals " and in the greater size—neither of which is a reliable feature for specific separation.

The ornament of the dermal bones consists of tubercles which are low and rounded, often grouped in short irregular rows and confluent at the base. The size of the tubercles on the posterior half of the " frontals " is rather larger than elsewhere, and in general the tubercles are larger along the top of the head than on the lateral parts of the skull roof. On the posterior part of the " frontals " the tubercles are very sparse mesially, and in general they are not abundant near the inter-" frontal " suture. The boundary between " frontals " and " postrostral " is marked by a row of small, densely crowded tubercles on either side of the suture.

The anterior pit-line is well shown on the right side ; it is sharply bent and quite short ; the sharp angularity is directly over the centre of radiation of the " frontal ".

This fine skull fragment is in some ways difficult to compare with other species of *Eusthenopteron* because of the different methods of preservation, but it is at once separable from *E. foordi* and *E. säve-söderberghi* by the very posterior position of the pineal foramen. No valid comparison with *E. wenjukowi* (Rohon) can be made, but it is interesting that the Upper Old Red Sandstone of Scotland includes a species of *Eusthenopteron* not greatly inferior in size to the Russian species. It is noteworthy that the new specimen has its pineal foramen even more posteriorly placed, proportionally, than has the holotype of *E. traquairi*, and it is possible that this difference is a progressive evolutionary feature. The remarkable size of the overlap area once covered by the " supraorbital " is very striking ; Jarvik (1937, p. 89) has pointed out that *E. säve-söderberghi* differs from *E. foordi* in the more elongated nature of the " posterior supraorbital ", but the conditions in this new skull are even more extreme. It is unfortunate that the conditions in the " supraorbital " region in the holotype of *E. traquairi* are unknown, but the shape of the " fronto-ethmoid " shield and the position of the pineal foramen favour the tentative reference of the new specimen to that species.

III. NOTES ON BONE NOMENCLATURE

The writer has previously (1936, p. 164 ; 1937, p. 517) made certain criticisms of the systems of bone-homologies suggested by the Swedish group of workers on fossil fishes, notably Stensiö, Jarvik (1937), and Säve-Söderbergh (1932, 1934, etc.). The modifications suggested previously have been very completely substantiated by the structure of the recently discovered *Elpistostege* (Westoll, 1938), which is intermediate between Crossopterygii and Tetrapods. Tetrapod bone-names can now be used in the study of Rhipidistian skulls, as shown in the following comparative table.

Rhipidistian names.		*Tetrapod names.*
Premaxilla, dentigerous rostral	=	Premaxilla
Nasal series	=	Nasal + Frontal
Frontal	=	Parietal
" Posterior antorbital," Antorbital	=	Prefrontal
" Anterior antorbital," Postnarial	=	" Anterior antorbital " (rare)
Postrostrals	=	Internasal, interfrontal
Supraorbital	=	Postfrontal
Parietal	=	Post-parietal (= dermo-supraoccipital)
Dermosphenotic	=	Intertemporal
Intertemporal	=	Supratemporal
Supratemporal	=	Tabular
Extrascapulars	—	(Not represented)
Extratemporals	—	(Not represented)
Operculars, gulars	—	(Not represented)

The following terms, used in both groups, seem to imply correct homology: Maxilla,[1] lacrimal,[1] jugal, postorbital, squamosal, quadratojugal, preopercular (only in Ichthyostegids among Tetrapods). The homology of the tetrapod septomaxillary in Crossopterygians is a little uncertain; it has usually been homologized with the Rhipidistian "anterior antorbital" (for which the writer suggested the term post-narial because of the incorrect homology with the antorbital of *Amia*). However, Jarvik (1937) has suggested that it is the homologue of the bone he called "lateral rostral", which the writer has termed pre-narial (1937, pp. 518–19). The arguments used previously in opposing the term "lateral rostral" have been fully confirmed by the writer on other material, but Jarvik's suggestion that this bone is homologous with the Tetrapod septomaxilla is almost certainly correct.

The long "nasal series" and the "frontal" of a Crossopterygian include the homologues of the Tetrapod nasals, frontals, and parietals. The most generalized condition in the Choanata was probably one in which the latero-sensory canals of the head were associated with a large number of small ossicles, usually one to each sensory organ; in these series fusions of adjacent small groups became common, and by differential growth at the expense of interstitial anamestic bones (Westoll, 1936, p. 166), there were evolved certain larger elements (e.g. frontals, parietals, nasals, of Tetrapods). The Rhipidistians show this tendency towards enlargement of the lateral-line bones in the interorbital regions (the so-called "frontals"), but very little trace of it is normally to be seen in the pre-orbital region. On the other hand *Elpistostege* and the Tetrapods show how easily it could be extended into the pre-orbital region to form the Tetrapod frontals and nasals. It should be remarked further that the primitive dependence of certain dermal bones on the latero-sensory canals, shown among the Choanata in primitive Dipnoi, Rhipidistia, and apparently in Ichthyostegalia, is not found in Stegocephalia; in the Tetrapods generally the bones have come to have an integral part in the architecture of the skull, instead of being a mere surface-plating. This functional importance has had the effect of "freezing" and fixing an arrangement of bones which was to a great degree correlated with the development of the latero-sensory canals, and which may legitimately be regarded as dependent on the influence of those structures. The subsequent evolution of the

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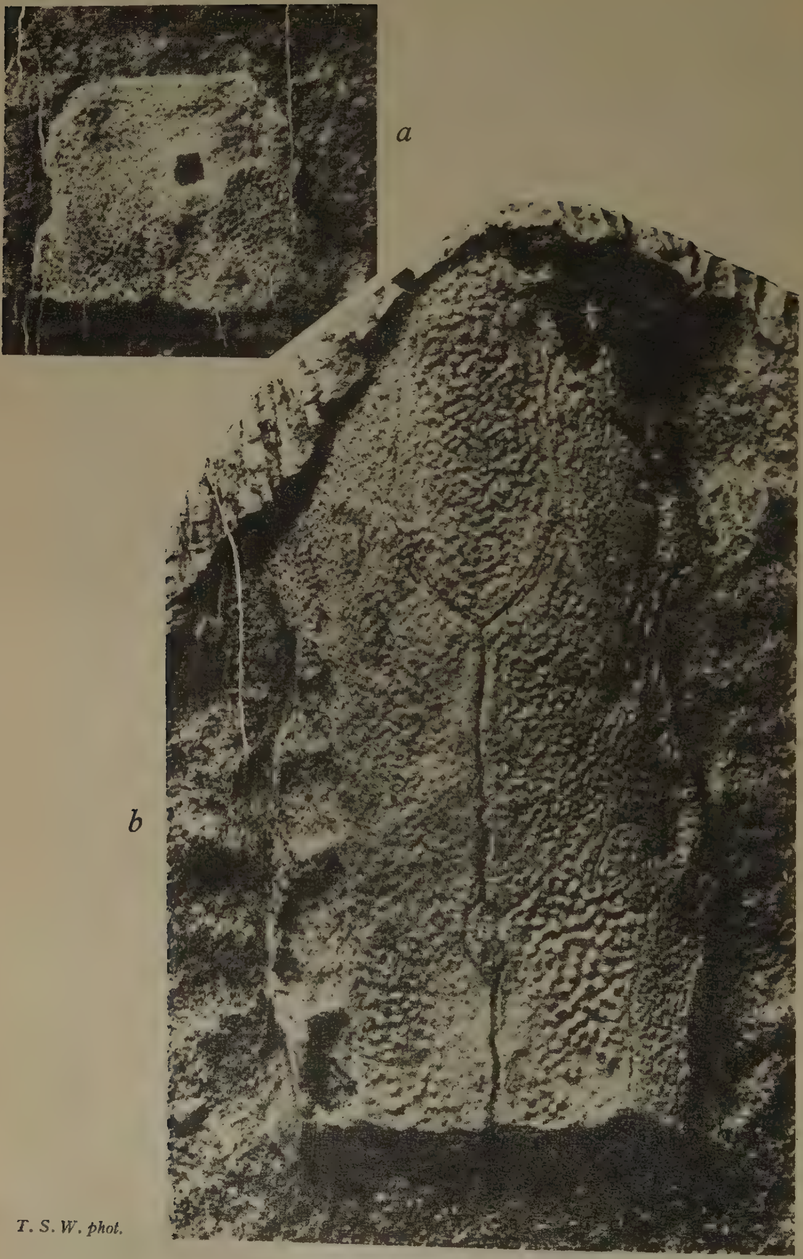
[1] These terms are used instead of the longer maxillary (maxilla = os maxillaris) and lachrymal (lacrima being the usual Latin form for a tear).



T. S. W. phot.

EUSTHENOPTERON

Tetrapod skull-pattern is essentially the history of the further adaptational modification of this structural pattern.

The application to fish-skulls of bone-names, derived primarily from Tetrapod bone-names, has been shown by the writer to have led to very many difficulties and wrong interpretations. It is not feasible to apply to all bony fishes the nomenclature of a specialized group of descendants of one stock, and it will probably be most convenient, for some time to come, to use the current nomenclature with the appropriate qualification—e.g. Rhipidistian supraorbital, Actinopterygian parietal. In this way it will be found possible in due course to make a comparatively painless change to a new nomenclature for bony fish skulls, not based on Tetrapod homologies.

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EXPLANATION OF PLATE II

A. *Eusthenopteron traquairi* Westoll. "Parietal" shield, × 1·4. Royal Scottish Museum, 1903, 63, 95.

B. *Eusthenopteron cf. traquairi* Westoll. "Fronto-ethmoid" shield, × c. 1·3. Plaster-cast of natural mould, Royal Scottish Museum.

An Occurrence of Detrital Diaspore in South Wales

By J. C. Griffiths and Alan Stuart

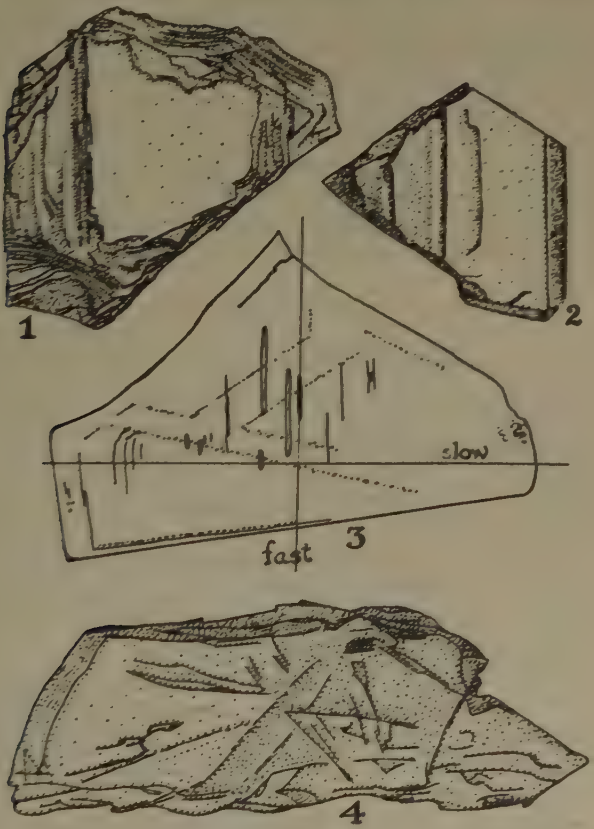
DURING the course of a petrological investigation by one of us (J. C. G.) of the glacial deposits in South-West Wales, samples from a sandy boulder clay at Ludchurch in South-East Pembrokeshire were found to contain abundant grains of a platy colourless mineral with a specific gravity greater than 2·9, a perfect pinacoidal cleavage and high double refraction. This was ultimately diagnosed as diaspore, with which were associated various iron ores, zircon, rutile, chlorite, various tourmalines (brown, green, and pink being the commonest), pyroxenes, amphiboles, staurolite, kyanite, brookite, anatase, topaz, garnet, apatite, muscovite, and andalusite, an assemblage typical of the Irish Sea Drift of this district. A search through the literature for a description of detrital diaspore showed that there did not appear to have been published any detailed description with figures of the detrital forms.

As the grains discovered at Ludchurch showed some interesting features it was thought that this occurrence merited description.

Boswell (2) records diaspore in his list of rock-forming minerals found in sedimentary rocks, and it has been recorded in detrital deposits by Berg (1), Branner (3), Chelussi (4), Damour (5), Ricciardi (10), Ries and others (11), Somers (12), Tucan (13), and Uzielli (14). In each of these cases, however, only the bare "text-book" properties by which the mineral was identified are given.

The mineral from Ludchurch occurs in colourless plates up to 0·4 mm., maximum diameter, lying parallel to the perfect (010) cleavage, with indications of a second cleavage probably parallel to the (210) (Text-figs. 1 and 2). In addition to the properties already mentioned grains are non-pleochroic, show straight extinction along the trace of the (210) cleavage, and have the optic axial plane parallel to the perfect (010) cleavage and the fast direction parallel to the trace of the (210) cleavage. The refractive indices determined in sodium light by the single variation immersion method (7), are: $\alpha = 1 \cdot 702$, $\beta = 1 \cdot 722$, $\gamma = 1 \cdot 748$, all $\pm \cdot 001$.

A study of the literature shows that whereas there is close agreement as to the values of α and β as given above, the values for γ vary from Berg's value (1) of $1 \cdot 752 \pm \cdot 003$, and $1 \cdot 750$ (all textbooks—6, 8, 15—following Schemnitz, Levy, and Lacroix) to Kerr's value (9) of $1 \cdot 742 \pm \cdot 003$. The textbook values are anomalous with the value for $2V$ quoted, viz.: 84° 20′ (which value is probably after Des Cloiseaux through Dana) as $2V$ calculated from the refractive indices is 81° 40′. Yoshiki (16) gives 1·747 for γ calculated from α, β, and $2V$. We found γ to be definitely above but very near to this last value and below 1·750. Yoshiki's value for $2V\gamma$, measured on a



Typical grains of detrital diaspore from Ludchurch, Pembrokeshire (× 200).

Hutchinson universal apparatus, is 84° 24′ for very pure material which compares very well with that of Des Cloiseaux. If the agreed values for α and β are used with Yoshiki's $2V$ to calculate γ, this works out to 1·7474, agreeing closely with our measurement. The value 1·752 ± ·003 must, therefore, be too high and Kerr's value, 1·742 ± ·003, too low for pure material at least.

Lines of abundant indeterminate black and pale yellow inclusions occur—some elongated parallel to the trace of the second cleavage (210) on the (010) face. These lines of inclusions are sometimes arranged according to a geometric pattern which is emphasized between crossed nicols by certain regular areas showing different polarization colours (Text-fig. 3). The angles which these lines of inclusions make with the trace of the (210) cleavage on (010) show that they commonly follow certain crystallographic directions. For example, angles measured from the trace of this cleavage, i.e., the direction of the *c* axis, lying around the values 38° and 57° represent traces of planes (2?1), and (1?1) on (010) respectively; and angles of 66° and 48° the bisectrices of which lie normal to the trace of the (210) cleavage represent the directions (1?1) and (2?3) respectively on (010). Crystal fragments commonly show shapes indicative of fracture along these lines (Text-figs. 1 and 2).

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REVIEW

INTERNAL CONSTITUTION OF THE EARTH. Physics of the Earth. VII. Edited by B. GUTENBERG. pp. x + 413. McGraw-Hill Publishing Company, Ltd., London, 1939.

This book is of great importance as affording a summary by the best authorities of the present state of knowledge in its subject. All the writers are now working in America except Dr. Jeffreys of Cambridge and the late Dr. H. S. Washington, whose posthumous contribution has been edited by Dr. L. H. Adams. Of the sixteen chapters, nine, including the summary, are by Professor B. Gutenberg, the editor of the book. The treatment is of course mainly geophysical, but such as can be easily followed by geologists: many chapters are entirely non-mathematical.

Dr. Jeffreys gives a clear almost popular discussion of the possible origins of the solar system, dealing with the various modifications of the near-approach and collision theories. He apparently inclines to the view that the sun was once a double star and that the collision was with the companion, not with the present sun. No writer in the whole volume has a good word for planetesimals, which may be considered as defunct.

The domain of the geologist really begins with the formation of the Earth's first permanent crust. There is nothing to show how much material crystallized and sank before any permanent crust was formed, but it may be noted that this simple sinking would itself set up currents in the substratum which would be difficult to stop. Everyone now seems to be agreed that the separation of the sial and sima can be explained by simple gravitational differentiation (crystal sinking).

Professor R. A. Daly contributes a chapter on the geophysical lessons to be learnt from pure geology: no one is more competent than he to deal with this side of the subject. Among other points he stresses the difference of attitude, structure, and crystallinity between the basement complex and the sedimentary veneers of later Precambrian and subsequent date, contrasting the steep dips, intense compression, and high degree of metamorphism of the former with the simpler and less altered condition of the latter outside the orogenic belts. Quite naturally also he accentuates his own conception of the vitreous basaltic substratum as a lubricant on which the continents can slide.

One of the most significant chapters is that by the editor on the structure of the crust and on the origin of the continents and oceans : in this again the conception of continental sliding plays a prominent part. Gutenberg's attitude towards continental drift is philosophical : he admits that there is much evidence for its occurrence, but no proof as to how it was brought about. He favours what he calls sliding of continents rather than drifting, though the distinction is not perhaps quite clear : he even gives a series of maps showing the positions of the continents at various dates, which bear a strong family likeness to Wegener's well-known diagrams, though differing much in detail. According to these, most of the land areas (Pangaea) started in the southern hemisphere and drifted or slid northwards.

Much space is naturally devoted to a discussion of the temperatures prevailing within the earth and to its heat content as a whole. An investigation by Van Orstrand of the U.S. Geological Survey leads to the result that the temperature gradient varies locally from 15° to 35° C. per kilometre, the average being about 20°. According to this the accepted gradient for the British Isles, 1° C. per 100 feet or about 33° per kilometre, is considerably steeper than the average. It is concluded that most of the heat lost by the earth comes from radioactivity. The excess of heat may be partly dissipated by subcrustal currents, with mountain-making as a by-product, but estimates of the actual radioactivity of the whole earth are not yet precise enough for positive statements. If there is as much as some geochemists believe it should be getting hotter, but as Gutenberg points out, on the evidence of contraction many geophysicists think it must be cooling. Here it may be pointed out, as it is hardly made clear anywhere in the book, that the evidence from geology shows average uniformity with spasmodic fluctuations ever since at any rate the late Precambrian. Biological evidence yields no support to the idea that in the Cambrian the earth as a whole was noticeably hotter than now. However, the occurrence of great local climatic variations is fully recognized and this naturally suggests possible variations in the position of the poles in relation to the continents. It is concluded that actual shifting of the earth's axis is not possible, but that sliding of the crust relatively to the axis is feasible as an explanation of past climatic variations.

In the whole discussion much importance is attached to the role of subcrustal currents, however generated. Even ordinary isostatic rising and sinking would cause a current of some sort and the recent study of deep focus earthquakes in certain parts of the earth shows that relative movement can take place down to depths of at least 700 kilometres. The general conclusion seems to be that thermal contraction plays an important though not the dominant part in the tectonics of the earth and the existence of subcrustal currents is receiving more and more recognition as the agent of continental displacement, formation of mountains and deeps, and changes of climate ; in short, the major incidents of historical geology.

R. H. R

ANNOUNCEMENT

Clough Memorial Research Fund

The fund was instituted in 1935 for the purpose of encouraging geological research in Scotland and the North of England. The North of England is defined as comprising the counties of Northumberland, Cumberland, Durham, Westmorland, and Yorkshire. Under the terms of administration of the fund a sum of approximately £30 is available annually.

Applications for grants are invited for the period 1st April, 1940, to 31st March, 1941. These applications should state :—

1. The nature of the research to be undertaken.
2. The amount of grant desired.
3. The specific purpose for which the grant will be used, e.g., travelling expenses, maintenance in the field, excavation of critical sections, etc.
4. Whether any other grant-in-aid has been obtained or applied for.

Applications must be in the hands of the Secretary, Clough Research Fund Committee, Edinburgh Geological Society, Synod Hall, Castle Terrace, Edinburgh, not later than 1st March, 1940.

REPORTS AND PROCEEDINGS

The Council of the Geological Society of London has made awards as follows :—

The Wollaston Medal to Henry Woods, in recognition of the value of his researches into " the Mineral Structure of the Earth ", especially his studies of fossil mollusca and crustacea from the Cretaceous formations of Great Britain, Africa, and New Zealand.

The Murchison Medal to Professor Arthur Holmes, in recognition of the value of his petrological researches and of his stimulating studies concerning the composition and physical state of the earth's interior.

The Lyell Medal to Professor Herbert Leader Hawkins for his eminence in palaeontology, particularly in his studies of the Echinoidea, and for his researches in Eocene stratigraphy.

The Wollaston Donation Fund to Miss Dorothea M. A. Bate for her investigations of Pleistocene mammalian faunas in Palestine and the Mediterranean.

The Murchison Geological Fund to Archibald Gordon MacGregor, for his petrological researches into Scottish rocks and his work on the geology of Montserrat.

A moiety of the Lyell Geological Fund to Miss Dorothy Hill, for her researches on Palaeozoic corals.

A second moiety of the Lyell Geological Fund to Laurance Henry Tonks, for his work on the Carboniferous rocks of Lancashire and Northumberland.

GEOLOGICAL MAGAZINE

VOL. LXXVII. No. 2. MARCH APRIL, 1940

EDITORIAL

AT the beginning of 1940, all rights in the *Geological Magazine* were transferred to Messrs. Stephen Austin and Sons, who have printed the Magazine for over 70 years. It was decided to take advantage of this change of publishers to adopt a new paper, new type, and a newly-designed cover. As a result of these changes, which involved among other things resetting several articles already in type, the January-February number of the Magazine had to be set-up very hurriedly and no opportunity was afforded for an editorial introductory to the new regime.

As was indicated towards the end of last year, it has been decided to issue the Magazine bi-monthly, chiefly because under war conditions contributions tend to reach us rather irregularly. The question of reverting to monthly parts will be reconsidered when conditions become more normal, but it may be pointed out that monthly publication does entail higher costs of production and distribution. We wish here to explain, however, that the bi-monthly numbers are designed to consist of not less than 80 pages, and that every effort will be made to maintain the size of the annual volume. While this arrangement holds, publication of the *Geological Magazine* will be due on the first day of alternate months, beginning with 1st February.

It is possible that, under present conditions, there may be some falling off in the output of original research, especially by the younger workers. The editors hope, therefore, to induce some of the leading authorities to contribute review articles in the form of summaries, with discussion and criticism, of the present trends of work and opinion in both general and specialized branches of geology.

The editors wish to express their gratitude to Messrs. Stephen Austin and Sons for their most helpful co-operation in these difficult times, as well as to subscribers, old and new, who are keeping the Magazine in being.

R. H. R.
O. M. B. B.

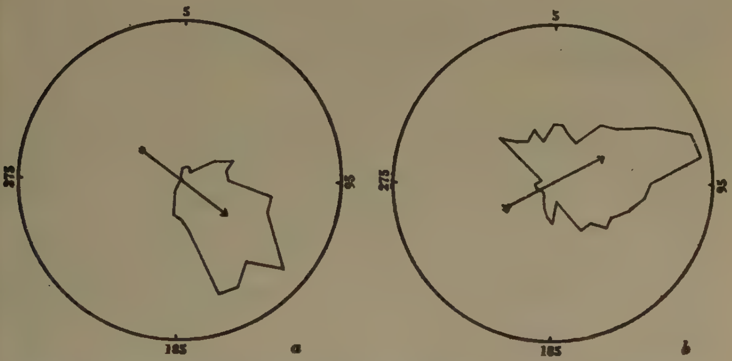
On the Direction of Certain Valleys

By K. Harrison and A. D. Thackeray

IN 1907 there appeared a memoir by F. W. Harmer, in which he suggested that a number of gorges—those at Malton and Ironbridge among them—might have originated as spillways consequent upon the blocking of the natural line of drainage by glaciers. A few years previously, Professor Kendall (1902) had interpreted some abandoned valleys in Yorkshire on the same hypothesis; a further exposition was given by Kendall and Wroot in 1924. In the present paper we propose a more fundamental origin for these channels.

Over a century ago John Phillips drew attention to a property shared by nearly all sedimentary rocks—the jointed structure: and he was not alone in supposing that denudation would take place in a preferential manner along joint-planes. The work of Kinahan (1875) in Ireland and of Daubrée (1879) in France demonstrated the parallelism between joints and river courses, so that the relation became a commonplace in the text-books of those days. While there has since been a tendency among writers to forget this well-established fact, references to it are not altogether lacking at the present time. Thus Lake and Rastall remark: " Solution takes place most readily along joint-planes, which are rapidly enlarged, so that streams in limestone districts tend to run in gorges cut along the major joints " (1927, p. 65). Nevertheless, there seems to be little disposition to apply this principle. Orthodox glacial theory brushes it aside, treating every severed spur and every anomaly of drainage as evidence for marginal channelling or lake overflow. It is clear that features primarily due to running water directed by an ice edge should be independent of the rock structure; in proportion as we find that the so-called overflow channels are directed by joints, in like proportion we must suspect that they were modelled in pre-glacial or interglacial times. And it is important to discriminate between valleys really due to lateral drainage and those sculptured in the ordinary course of erosion; for the multiplication of imaginary glaciers helps to confuse a problem already confused enough—the stratigraphy of the Drift.

The simplest objective method of analysing preferential directions in a river is to divide the course into a large number of equal segments and form a polar frequency diagram of the directions ϕ of such segments. We have performed the analyses using 6 in. ordnance maps; dots or other symbols which mark administrative boundaries split the river into segments of convenient length (about 25 ft.). The directions ϕ have been measured from North clockwise, using a protractor, and arranged in groups of 10° (0–10, 10–20, etc.). Streams flowing through drift or alluvium will give roughly elliptical polar frequency curves (Text-fig. 1), the major axis of the ellipse pointing approximately in the direction AB, where A and B are the beginning and end of the measured portion of the stream. The shape of the ellipse depends upon the maturity of the river: an 11-mile stretch (840 segments) of the Ouse from Aldwark to York gives a less elongated figure than a 14-mile portion (1,110 segments) of the Nidd from Hunsingore to Nun Monkton, because the Nidd has reached its base-level and frequently meanders against the dip of the country.



Text-fig. 1.—Frequency of ϕ: (*a*) Ouse, (*b*) Nidd. The arrows indicate the general direction AB.

On turning to certain rivers which are supposed to course along glacial channels, however, the shape of the ϕ diagram is significantly altered (Text-fig. 2). Instead of a rough ellipse, a series of peaks and troughs emerges, indicating preferential lines of flow. Not all these are of equal significance. The general direction AB of the river tends to predominate, and, since the points A and B were arbitrarily selected in the first instance, some correction is necessary. The following method has been developed to allow for this.

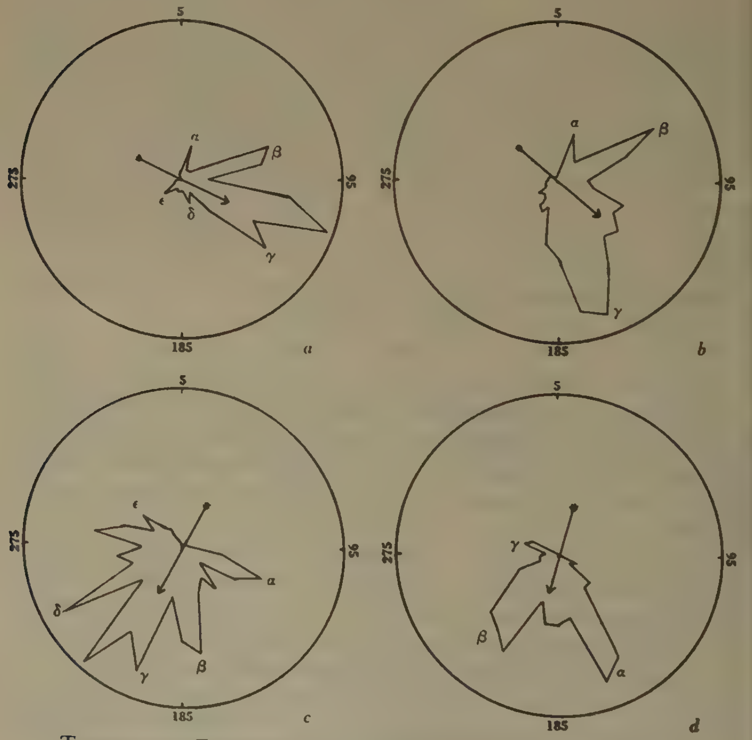
Consider a stream flowing between two points A and B (Text-fig. 3). Let the total length along the river be N units, and the distance AB as the crow flies, n units. PQ is any segment of unit length making an angle θ with the direction AB (which is taken as zero direction). The vector PQ may be regarded as the resultant of two components :—

(i) A systematic component PR, length n/N in the direction AB.

(ii) A random component PR′, which has a direction θ' with respect to AB given by—

$$\frac{\sin\theta'}{1} = \frac{\sin(\theta'-\theta)}{n/N} \qquad (1)$$

$$\text{and magnitude PR}' = \text{QR} = \frac{\sin\theta}{\sin\theta'} \qquad (2)$$



TEXT-FIG. 2.—Frequency of ϕ : (*a*) Wharfe, (*b*) Ure, (*c*) Derwent, (*d*) Newtondale.

The random components PR′ placed end to end will form a closed curve because of the imposed conditions that PR = n/N in the direction AB. The directions θ' of the components PR′ should, therefore, occur at random unless certain geological factors (such as joints, etc.) are present. Treated purely as a geometrical problem the most probable form of the polar frequency diagram of θ' is a circle.

Application of the method involves measurement of the ratio n/N for each river, and also the general direction AB (from which θ is measured). A table is then constructed relating ϕ with θ and θ', by means of equation (1), and a frequency table of θ' set up, using the observed ϕ directions. Finally, these frequencies are weighted according to $\sin\theta/\sin\theta'$, from equation (2). The resulting θ' diagrams are given in Text-fig. 4. After selecting the significant peaks (marked with Greek letters), reference to the ϕ diagram enables the predominant directions to be read off.

Even in the θ' diagrams there is a significant deficiency of directions opposed to AB; there must, therefore, be geological factors which destroy the analogy with the purely geometrical problem—for example, the directions of successive segments are related to one another in the sense that a river tends to change its course gradually rather than abruptly. However, attempts to allow for this would involve considerable labour, and it seems unlikely that the directions or magnitudes of the peaks, with which we are here concerned, would be materially altered.

In addition to the rivers, results for two dry channels, Newtondale and Low Lindrick, are given in Table I; the figures within brackets represent the relative weights (determined approximately from the θ' diagram) of the directions. The experimental error involved in the measurements and calculations is about ± 3°.

TABLE I

	Number of segments.	*Preferential directions.*								
R. Wharfe (Wetherby to Newton Kyme) .	420	25° (2)		53° (1)		80° (2)	114° (1)	133° (1)		
R. Ure (Clifton to West Tanfield). . .	680	24° (1)			65° (2)				166° (2)	
R. Derwent (Huttons Ambo to Howsham).	480	25° (1)			63° (1)		112° (3)	135° (2)		179 (1)
Low Lindrick . .	150								163° (3)	
Newtondale . .	820		43° (2)				116° (2)		163° (3)	

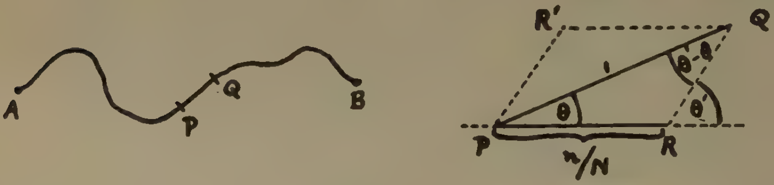
Now Melmore (1938), on the basis of over 200 measurements (corrected for magnetic variation), has found that the joint-planes (of the Magnesian Limestone, Millstone Grit, and

Corallian of the area in which these channels occur) arrange themselves into five well-defined classes, of which the arithmetic means are

24°, 55°, 84°, 115°, and 163°.

These directions occur far too frequently in Table I to be merely accidental. The directions 25°, 115°, and 163° are especially predominant, accounting for more than half of the total, and the inference must be that all these valleys, whether occupied by rivers or not, are controlled by joints. A few supplementary notes will help to make clear the significance of these findings.

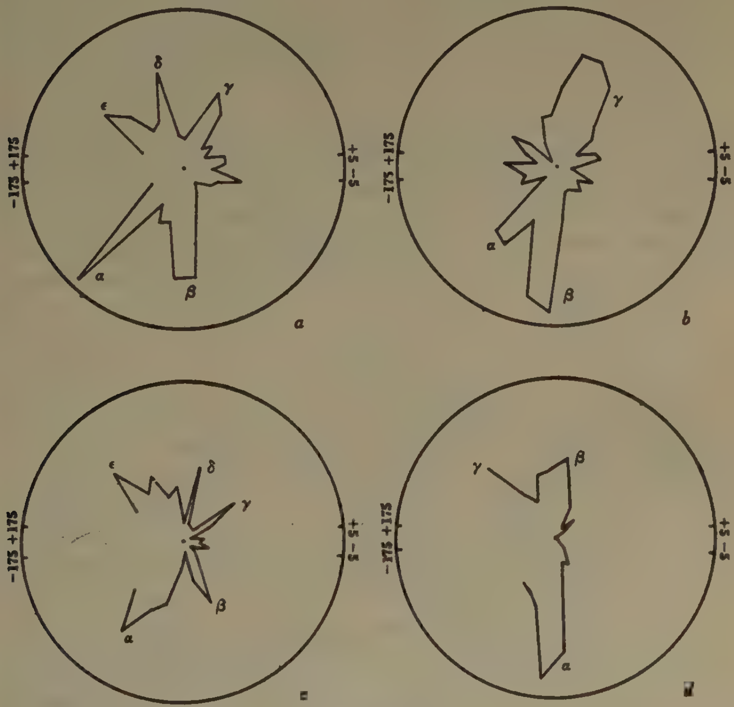
R. Ure.—In the opinion of Raistrick (1926), the valley of the Ure below Clifton Castle is due to erosion by a northern tributary of the River Burn: he supposes that the Ice Age came on before this tributary had time to capture the preglacial Ure, which was flowing due east from Leyburn. There is, however, no evidence to show that the tributary of the Burn did not capture the Ure, in a normal fashion, before the glaciation began (Melmore, 1935, p. 67). The case of the Wharfe is more obscure, as it is doubtful whether the catchment area south of Wetherby is large enough to have developed a capturing river.



TEXT-FIG. 3.

Low Lindrick.—This almost straight channel is bounded on the east by what appears to be a moraine, but from the fact of the channel's following a joint-plane we cannot be sure that glacial drainage did more than deepen a trough already in existence. A very careful discussion of the problems which arise in this district is given by Melmore (1935) and by Gayner and Melmore (1937).

Newtondale.—"The most striking feature of Newtondale," say Kendall and Wroot (1924, p. 501), "whether we view it as a whole upon the map, or travel through it by train, is its curiously winding course. . . . Evidently the volume of water which cut it was sufficient to obey the laws of meandering, though on a gigantic scale. The banks of normal rivers meander within their valleys. Here the trench itself meanders as it cuts its way across the upland plain." There is some confusion of thought in these remarks. The meandering of a river is due to causes entirely distinct from those which shape the direction of its valley. Analysis shows that the course of Newtondale is governed by planes at 163°, 116°, and 43°. Fox-Strangways (1892, p. 419), after a survey of the ground, was of the opinion that the channel resulted from normal fluviatile erosion. Professor Bonney (1915, pp. 13–14) reached the same conclusion, holding that the dale was preglacial and carved out by Eller Beck and other streams which formerly ran into the Vale of Pickering.



TEXT-FIG. 4.

The Malton Gorge.—The figures for the Derwent likewise confirm the view of Fox-Strangways (1892, p. 423) that an earlier stream, draining northwards into the Vale of Pickering, existed on this site: " it may be that the whole channel from Malton to Stamford Bridge is due to river capture, as between this ancient stream and another flowing into the Vale of York " (Melmore, 1935, p. 34).

So far we have been considering a district which is covered by field measurements of joint directions. These cannot be expected to hold good in all areas, particularly where there has been considerable tectonic disturbance. Thus, Wager (1931) finds that the master joints in the Carboniferous Limestone of north-west Yorkshire are 55° E. of N. and 145° S. of E.: and he observes that " the drag due to the relative horizontal movement along the faults has caused a local modification of the joint directions in the neighbourhood of the faults ". It would be unprofitable, then, to carry out analysis of river courses in districts where evidence from the field is not available. For this reason we have confined ourselves to examples from central Yorkshire.

Reference must be made, in conclusion, to Melmore's work (1935, pp. 62–9) on similar valleys in Yorkshire—the Knaresborough Gorge, Cayton Gill, and the valley of the Skell: he considers that all these channels, since they follow joint directions, were in existence before the glaciation. The mathematical findings set out in this paper lend further support to his thesis.

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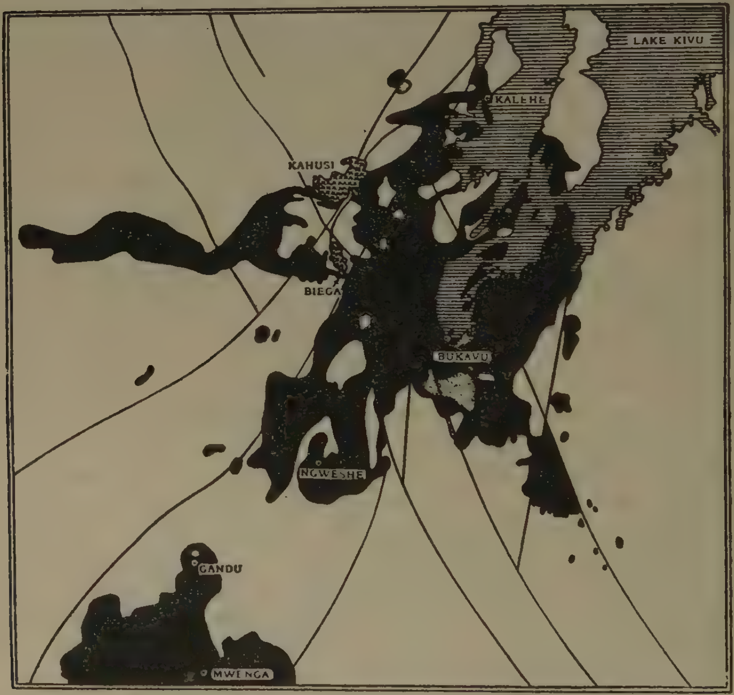
Basaltic Lavas of South Kivu, Belgian Congo

By Arthur Holmes, University of Durham

In a recent memoir (Holmes and Harwood, 1937, p. 276) I had occasion to point out that " one of the most remarkable features of the igneous activity of late Cretaceous and early Tertiary times is the geochemical and petrological contrast between the kimberlite and olivine-melilitite which perforated the crust of Southern Africa and the widespread outpourings of olivine-basalt and basalt (often followed by acid rocks) in many other parts of the world ". An essentially similar contrast is found in the more recent and more localized volcanic fields of the Western Rift of Africa. The Toro-Ankole fields of multiple vents, east and south-east of Ruwenzori, are characterized throughout by undersaturated potassic types, free from felspar ; whereas in the great lava fields south of Lake Kivu the dominant lavas are olivine-basalts of various types. Between these two strongly contrasted provinces, and in some respects sharing the characters of each, the Birunga field (including Bufumbira) extends across the Rift north of Lake Kivu. Although many of the lavas of this field contain abundant plagioclase and look like basalts, they have been found, with few exceptions, to be potassic types ranging from leucite-basanites to basanitoid trachybasalts. True basalts appear to be absent (Holmes and Harwood, 1937, pp. 16–18), the nearest approach to basalt —geographically as well as petrographically—being certain trachybasalts and limburgites from the south of the field, which differ from the other rocks of Birunga in having more soda than potash.

In view of the fact that some of the Birunga lavas were originally thought to be olivine-basalt, though later found to contain from 1·92 to 4·09 per cent of potash, the possibility should not be overlooked that a similar mistake may have been made in determining the basaltic rocks—or some of them—from the South Kivu fields. The possibility has been raised for discussion by Bowen, who writes in a recent paper (1938, p. 29) : " The basaltic lavas have been described as ordinary olivine-basalts but in specimens of adequately coarse crystallization it can be made out that there is a feldspar of index lower than balsam in the groundmass (anorthoclase) and the rocks would be more adequately described as trachydolerites." Bowen's diagnosis is likely to be correct for the specimens which he collected, but the implied generalization is not justified. The object of this communication is to show that true olivine-basalts do occur in the South Kivu fields.

The South Kivu volcanic areas have been extensively explored in recent years by the geologists of the Mission Géologique du Comité National du Kivu (Boutakoff, 1933 and 1939), and an excellent geological map of the region is now available (Asselberghs, 1939). As described by several petrologists, beginning with Passau (1932), the lavas are dominantly basaltic, and nearly all are olivine-bearing ; they cover a total area of about 5,500 sq. kms. As shown on Text-fig. 1, two main independent areas have been recognized : one immediately adjoining the south and south-west shores of Lake Kivu, where the Albertine and Tanganyikan rifts meet in a tectonic culmination ; the other, farther south, around Mwenga and Gandu, in a depression that



Text-fig. 1.—The volcanic fields of South Kivu, after the *Carte Géologique de la région du Kivu au 500,000*^{e} (Asselberghs, 1939, Plate v). Basaltic lavas, solid black ; trachytes, dotted ; rhyolites and quartz-porphyries of Kahusi and Biega, crosses. Scale : 1 in. = 20·8 miles.

continues the Albertine rift direction beyond the South Kivu culmination.

Most of the basalts of the first of these areas came from two centres high up on the western wall of the rift: (*a*) the crater of Kahusi, now reduced by erosion to a neck of microdolerite, about 2 km. across, which is still laterally connected with the latest basaltic flows; and (*b*) a series of fissures which opened in the grano-syenite complex of Biega, south of Kahusi (see Sorotchinsky, 1934, pl. vi, for detailed map). From each centre voluminous emissions of basaltic lavas flowed west into the Congo cuvette, eastwards into the Kivu and North Tanganyikan rift depressions, and south into the Ngweshe depression. The flows followed the existing valleys and are, therefore, not very old, but erosion has deeply etched the surface, and weathering to lateritic red earths is widespread. In the Ruzizi valley the lavas are locally covered by the Panzi beds, the lower part of which is of Lower Pleistocene age. The basaltic lavas are therefore probably of Pliocene age.

Trachytes, ranging from trachyandesitic to phonolitic types, occur in three main areas: south of Bukavu, east of Bukavu, and west of Kalehi (see Text-fig. 1). In the first of these the present channel of the Ruzizi, in which the Panzi beds were deposited, is cut in trachyte as well as basalt, indicating that this occurrence of trachyte is older than the Panzi beds. In the second area veins of trachyte cut lateritized basalt, indicating that here the trachyte is post-basaltic.

Long after the basaltic flows, rhyolites were erupted from both Kahusi and Biega. No trachyte has been found associated with these centres, but as similar rhyolite, petrographically like that of Biega, cuts the Panzi beds, it is inferred that the rhyolite phase followed the trachyte phase. At Kahusi the first rhyolite phase was succeeded by a series of rhyolites and quartz-porphyries characterized by abnormally high potash and silica (Sorotchinsky, 1934).

The basalts of the Gandu-Mwenga area appear to be somewhat older than those of the Kahusi-Biega field. They have been more maturely dissected by denudation and their covering of red earths and soil is considerably thicker. No more exact information of their age is available.

According to Kazmitcheff (1936, pp. 37–40), who has briefly described eleven specimens from this southern area, together with a few similar rocks from the Kahusi-Biega field, the basalts are fine-grained and often vesicular, and are composed of the usual minerals: labradorite, augite, and black ores, generally, but not always, accompanied by olivine. Most of the specimens are porphyritic, the phenocrysts being olivine and augite, usually with labradorite or glomeroporphyritic groups of labradorite in addition. The texture of the groundmass is microtrachytic to intergranular. The vesicle-minerals are carbonates of various kinds. Some of the Gandu-Mwenga specimens, including one that has been analysed, contain sporadically distributed rounded xenocrysts of quartz with brown amorphous rims and fringes of more or less radially disposed prisms of augite. The analysed rock, which contains a little olivine, has the following composition :—

TABLE I

Basalt, S. 299, 15 km. N.W. of Mwenga, South Kivu. (Kazmitcheff, 1936, p. 40. See Pl. vi for locality.)

SiO_2	49·84	·8298	Quartz			2·71
Al_2O_3	14·13	·1386	Orthoclase			3·62
Fe_2O_3	4·19	·0262	Albite			14·89
FeO	9·63	·1341	Anorthite			28·84
MgO	7·78	·1930	Diopside	$CaSiO_3$	8·81	17·24
CaO	10·07	·1796		$MgSiO_3$	5·04	
Na_2O	1·76	·0284		$FeSiO_3$	3·39	
K_2O	·61	·0065	Hypersthene	$MgSiO_3$	14·33	24·00
H_2O	1·48	—		$FeSiO_3$	9·67	
TiO_2	·71	·0071	Magnetite			6·07
			Ilmenite			1·35
	100·20		Water			1·48
						100·20

Analyst : P. Ronchesne.

The rock is a basalt of the type distinguished by Daly (*Igneous Rocks and the Depths of the Earth*, 1933, p. 404) as " poor in alkalies ". As shown in Table II, it can be matched by examples of basaltic rocks, nearly all of which contain a little olivine, from the Karroo basalts and dolerites of Africa, the Triassic basalts of New Jersey, the Tertiary basalts of the Deccan, and the tholeiites of the North of England.

The basalts of the Kahusi-Biega field included by Kazmitcheff with the group described above are from localities north of Ngweshe and near Kahusi. Another collection has been described by Sorotchinsky (1934, pp. 23–7), who divides the specimens into two groups : (*a*) " basaltes à olivine " from localities south and west of both Kahusi and Biega ; and (*b*) " microdiabase ophitique " from localities south-west of Kahusi. The rocks of group (*a*) contain phenocrysts of olivine, often accompanied by colourless to pale purplish brown augite and/or labradorite. The groundmass has microliths of plagioclase and rounded grains of augite and olivine, together with black ores.

Those of group (*b*) are olivine-poor basalts with a fine-grained ophitic texture, prisms of labradorite up to 2 mm. long being partly enclosed in larger plates of colourless to pale brown augite. No chemical analyses are presented, but Sorotchinsky has made micrometric analyses of two examples of group (*a*) and from the mineral composition he estimates the chemical composition of each.

TABLE II

	A	B	C	D	E	F
SiO_2	49·84	49·50	51·94	51·09	49·38	50·07
Al_2O_3	14·13	13·91	15·21	14·23	13·49	14·53
Fe_2O_3	4·19	2·20	·99	2·56	3·67	1·76
FeO	9·63	9·60	9·06	7·74	8·94	8·26
MgO	7·78	6·48	7·00	7·56	6·48	6·77
CaO	10·07	10·92	10·49	10·35	11·26	11·50
Na_2O	1·76	1·94	1·50	1·92	1·68	1·93
K_2O	·61	·43	·86	·42	·72	·85
H_2O+	1·48	·90	·67	1·01	1·42	·82
H_2O-		·85	·47	1·66	·24	·52
CO_2	—	·07	—	—	—	1·61
TiO_2	·71	2·09	1·06	1·30	2·16	1·14
P_2O_5	—	·41	·27	·16	·46	·16
MnO	—	·15	·53	·25	·21	·19
Incl.	—	·51	—	—	—	·22
	100·20	99·96	100·05	100·25	100·11	100·33

A. Olivine-basalt, No. S. 299, 15 km. N.W. of Mwenga, South Kivu. Kazmitcheff, 1936, p. 40. *An.* P. Ronchesne.

B. Basalt, Karroo Lava IV, Victoria Falls, Southern Rhodesia. E. Golding, *Geol. Surv. S. Rhodesia, Bull.* **29**, 1936, p. 28. *An.* E. Golding.

C. Karroo dolerite, intrusive sheet, Dover Junction, Orange Free State. R. A. Daly and T. F. W. Barth, *Geol. Mag.*, **67**, 1930, p. 101. *An.* E. G. Radley.

D. Triassic basalt. Hartshorn's Quarry, Springfield, New Jersey, U.S.A. J. V. Lewis, *N.J. Geol. Surv., Ann. Rep. 1907*, 1908, p. 159. *An.* R. B. Gage.

E. Deccan basalt. Padmi, Mandla, Central Provinces, India. H. S. Washington, *Bull. Geol. Soc. Amer.*, **33**, 1922, p. 774. *An.* H. S. Washington.

F. Tholeiite (Brunton Type). Bingfield Dyke, Northumberland, England. A. Holmes and H. F. Harwood, *Min. Mag.*, **22**, 1929, p. 18. *An.* H. F. Harwood.

It will be seen that, so far, there had been no reason to suppose that the South Kivu basaltic lavas were other than typical olivine-basalts and basalts. Bowen, however, in support of his suggestion that " the rocks would be more adequately described as trachydolerites ", writes as follows (1938, p. 29) : " A specimen collected at the rapids at the outlet of Lake Kivu appears to be typical. It has phenocrysts of augite and olivine in a groundmass containing the same minerals with labradorite. This is zoned and passes to anorthoclase which is not abundant but forms a sort of mesostasis. Specimens of columnar lava from the shore of Lake Kivu about a mile north-west of Bukavu (Costermansville) are not significantly different. By reason of a mislaying of the specimens after chips had been sent off for thin sections it has not been possible to get an analysis of these trachydoleritic basalts. They show no significant microscopic differences from the trachydolerites of the North Kivu field but whether they would prove to be potash-rich or, on the other hand, soda-rich, like the basaltoid rocks of the Eastern Rift, is a question that has not been decided."

In view of Bowen's comments, it seemed desirable that chemical analyses should be made of some of the South Kivu basaltic rocks Representative specimens of the two groups distinguished by Sorotchinsky were kindly sent to me a few years ago by Professor J. Thoreau of Louvain University for comparison with the Birunga lavas. B. 246 is an example of group (*a*) and was collected from a locality about 2·5 km. a little west of south of the summit of Kahusi. B. 316 represents group (*b*) and is from the left bank of the Mukaba River, about 2·3 km. a little east of south of the summit of Kahusi. These have now been analysed and the results are presented below.

B. 316 is a fine-grained compact basalt of dark grey colour, sparsely variegated with small laths and aggregates of plagioclase up to 2 mm. in length. It has the general aspect of the more basic tholeiites of the North of England and in thin section it recalls at once the olivine-bearing Salen Type (Holmes and Harwood, *Min. Mag.*, **22,** 1928, 12–17), for, although it is holocrystalline sporadic intersertal patches of deep brown to greenish brown iddingsite simulate the tholeiitic type of mesostasis. Similar iddingsite, pseudomorphous after olivine, small cores of which remain unaltered, makes up 7 or 8 per cent of the rock. The augite is a very pale fawn variety and occurs in small irregular grains having an intergranular to (exceptionally) sub-ophitic relationship with plagioclase. The larger laths and aggregates of plagioclase are zoned marginally from about An_{70} to An_{45}, while the smaller laths, which build a typically unorientated plexus, range from about An_{60} to An_{45}. Black ores are scattered among the other minerals in skeletal rods and twig-like forms and occasional intersertal patches.

The chemical composition of B. 316 is given in Table III and comparison is made with other well-known basaltic rocks in Table IV. B. 316 is chemically very similar to S. 299 (Table I) from the Gandu-Mwenga field, the only noteworthy difference being the higher soda content. Like S. 299, it can be matched with examples of the Karroo dolerites of Africa ; the Triassic basalts and the Palisades Sill of New Jersey ; and the more basic tholeiites of the North of England. The combined evidence of Tables I and III demonstrates beyond further doubt that basalts of perfectly normal mineralogical and chemical composition occur in both the main fields of South Kivu.

B. 246 is a very fine-grained slaty grey rock with conchoidal fracture, containing small phenocrysts of olivine, generally about 1 mm. long, but occasionally two or three times as big. Part of the specimen contains minute amygdales filled with fibrous carbonates, partly calcite and partly a yellowish brown variety like that determined by Kazmitcheff (1936, p. 38) as belonging to the siderite-giobertite series (about 5 per cent $CaCO_2$; 21 per cent $FeCO_3$; and the rest mainly $MgCO_3$). Both in the hand specimen and in thin section the rock closely resembles the Hillhouse Type olivine-basalts of the Midland Valley.

TABLE III

Olivine-basalt, B. 316, Mukaba River, South of Kahusi, South Kivu

SiO_2	50·19	·8357	Quartz			1·71
Al_2O_3	14·56	·1428	Orthoclase			3·17
Fe_2O_3	3·19	·0200	Albite			21·23
FeO	8·05	·1121	Anorthite			26·86
MgO	7·22	·1791	Diopside	$CaSiO_3$	8·82	17·19
CaO	9·88	·1762		$MgSiO_3$	5·23	
Na_2O	2·51	·0405		$FeSiO_3$	3·14	
K_2O	·54	·0057	Hypersthene	$MgSiO_3$	12·75	20·41
H_2O +	1·68	—		$FeSiO_3$	7·66	
H_2O —	1·10	—	Magnetite			4·63
CO_2	none	—	Ilmenite			1·82
TiO_2	·96	·0120	Apatite			·32
P_2O_5	·11	·0008	Water			2·78
MnO	·13	·0018				
	100·12					100·12

Analyst : W. H. Herdsman.

Microphenocrysts of fresh olivine (negative with nearly straight isogyres in β-sections) are conspicuous, in rounded grains and occasional euhedral or subhedral forms (0·2 to 2 mm.). There is no sign of serpentinization, but many of the crystals have grey rims of extremely finely granular augite. The groundmass is rich in minute irregular grains and prisms of fawn to faintly purplish augite, associated with occasional blebs of olivine and abundant specks of sharply crystallized black ore. Tiny laths of labradorite form an open mesh with a suggestion of trachytic orientation here and there. Subordinate interstitial patches of a felsic mineral can be detected, having a refractive index slightly below that of balsam; these are probably alkali felspar. No nepheline or analcite has been recognized with certainty. A few rounded xenocrysts of quartz, mantled with radially disposed prisms of augite, occur and there are occasional patches of similar augite aggregates without cores of quartz.

TABLE IV

	G	H	I	J	K
SiO_2 . .	50·19	51·28	50·19	51·88	50·41
Al_2O_3 . .	14·56	15·03	14·65	14·53	15·14
Fe_2O_3 . .	3·19	·07	3·41	1·35	2·71
FeO . .	8·05	10·61	6·96	9·14	7·95
MgO . .	7·22	7·59	7·95	7·78	6·57
CaO . .	9·88	9·96	9·33	9·98	11·30
Na_2O . .	2·51	2·28	2·64	2·06	2·29
K_2O . .	·54	·74	·75	·93	·82
H_2O + . .	1·68	·59	2·38	·97	1·01
H_2O − . .	1·10	·14	·66	·12	·72
CO_2. . .	none	—	—	—	·07
TiO_2 . .	·96	1·17	1·13	1·35	1·30
P_2O_5 . .	·11	·29	·18	·14	·15
MnO . .	·13	·37	·07	·10	·17
Incl. . .	—	—	—	—	·19
	100·12	100·32	100·30	100·33	100·80

G. Olivine-basalt, B. 316, South of Kahusi, South Kivu. *An.* W. H. Herdsman.

H. Karroo dolerite, Intrusive Sheet, near Insizwa Mountain, South Africa. R. A. Daly and T. F. W. Barth, *Geol. Mag.*, **67**, 1930, p. 101. *An.* E. G. Radley.

I. Basalt, Lower layer. Hartshorn's Quarry, Springfield, New Jersey, U.S.A. J. V. Lewis, *New Jersey Geol. Surv. Ann. Rep. 1907*, 1908, p. 159. *An.* R. B. Gage.

J. Basaltic diabase of Palisades Sill, Weehawken, New Jersey. J. V. Lewis, *ibid.*, p. 121. *An.* R. B. Gage.

K. Olivine-tholeiite (Salen Type). Kielderhead, Northumberland. A. Holmes and H. F. Harwood, *Min. Mag.*, **22**, 1929, p. 15. *An.* H. F. Harwood.

The chemical composition of the rock is given in Table V. As compared with Sorotchinsky's estimates, referred to on page 93, MgO is considerably higher and Al_2O_3 and CaO are correspondingly lower; otherwise the agreement is fairly good. The analyses quoted for comparison in Table VI show that B. 246 is a basanitoid (Lacroix) or an essexite-basalt (Lehmann) which resembles examples from Madagascar and the volcanic field north of Lake Nyasa. It can be equally well matched by the Midland Valley olivine-basalts of Hillhouse Type (intermediate between olivine-basalt and monchiquite or basanitoid limburgite), and by related monchiquitic basalts from the same province. Approximately similar types occur among the basanitoid basalts of

Tibesti (Lacroix, *Mém. Acad. Sci., Inst. de France,* **61** (2), 1934, pp. 237–8) and Erythrea (*ibid.*, p. 345), but these, like some of the rocks of Table VI, contain more potash relative to soda than the essexite-basalt under discussion. The latter can hardly be described as a trachydolerite, but it might not improperly be claimed as a melanocratic member of a trachydoleritic series, and to this extent Bowen's diagnosis of the specimens from the neighbourhood of Bukavu is supported, especially as trachytes, representing the felsic end of such a series, also occur in the same neighbourhood.

TABLE V

Essexite-basalt (cf. Hillhouse Type), B. 246, near Kahusi, South Kivu.

SiO_2	43·56	·7253		Orthoclase		5·45
Al_2O_3	15·04	·1475		Albite		16·79
Fe_2O_3	2·74	·0172		Anorthite		23·54
FeO	8·84	·1231		Nephelite		5·89
MgO	8·01	·1987		$CaSiO_3$	9·80	
CaO	10·95	·1953	Diopside	$MgSiO_3$	6·16	18·97
Na_2O	3·28	·0529		$FeSiO_3$	3·01	
K_2O	·92	·0098	Olivine	Mg_2SiO_4	9·66	14·85
H_2O +	1·82	—		Fe_2SiO_4	5·19	
H_2O −	·84	—		Magnetite		3·98
CO_2	none	—		Ilmenite		5·35
TiO_2	2·82	·0353		Apatite		2·37
P_2O_5	·79	·0056		Water		2·66
MnO	·23	·0032				
	99·84					99·85

Analyst : W. H. Herdsman.

It is of interest to compare the South Kivu essexite-basalt with some of the lavas from the north end of Lake Kivu. As shown in Table VII, the nearest type as regards the alkalies is the limburgite, U, erupted from Nahimbi (formerly known as the Adolf Friedrich Volcano) in 1904–5. The other lavas, however, are relatively potash-rich. S and T, representing other recent eruptions, are remarkably similar to the essexite-basalt, R, except that they contain about three times as much potash.

The South Kivu basaltic rocks are, in fact, unusually poor in potash by any standard, and strikingly so in view of their occurrence in the Western Rift. The trachytes of South Kivu (Bowen, 1938, p. 29) also differ from those of Karissimbi in the Birunga field in having more soda than potash, though here the contrast is less marked. The rhyolites and quartz-porphyries of Kahusi and Biega, however, go far to the other extreme and are relatively more potassic than most of the lavas of Birunga and Toro-Ankole.

These facts are clearly brought out in Text-fig. 2, which gives a picture in terms of the alkalies of the three provinces of the Western Rift and so expresses in part the relationships and differences between them. It is noteworthy that the points representing the South Kivu rocks fall in every case outside the areas representing the other two provinces; the basalts and trachytes are more sodic, the rhyolites and quartz-porphyries more potassic.

TABLE VI

	L	M	N	O	P	Q
SiO_2	43·56	43·75	43·49	43·73	44·20	43·94
Al_2O_3	15·04	15·90	16·70	13·73	15·04	15·44
Fe_2O_3	2·74	2·50	4·17	2·74	1·56	3·90
FeO	8·84	7·85	9·09	8·87	9·52	8·25
MgO	8·01	9·34	8·20	8·33	10·26	9·64
CaO	10·95	11·10	10·05	10·76	10·13	10·56
Na_2O	3·28	3·38	2·72	3·06	3·46	2·81
K_2O	·92	·75	1·20	1·35	1·15	1·34
H_2O –	1·82	3·10	1·41	3·48	1·85	2·33
H_2O –	·84		·26	·48	·20	·19
CO_2.	none	—	—	·00?	tr.	—
TiO_2	2·82	2·40	1·90	3·22	1·95	2·03
P_2O_5	·79	·07	·68	·37	·32	—
MnO	·23	—	—	·16	·14	tr.
Incl.	—	—	—	·12	—	—
	99·84	100·14	99·87	100·40	99·78	100·43

L. Essexite-basalt, B. 246, South of Kahusi, South Kivu. *An.* W. H. Herdsman.

M. Basanitoid or Essexite-basalt, Ampombilava, Nosy Be, Madagascar. A. Lacroix, *Min. de Madagascar*, iii, 1923, p. 56, No. 391. *An.* A. Pisani.

N. Essexite-basalt, east of Kiejo, North Nyasa volcanic field, Tanganyika Territory. E. Lehmann, *Zeit. f. Vulk.*, *Erg. Bd.* **4**, 1924, p. 125. *An.* Klüss.

O. Olivine-basalt, Hillhouse Type, Carboniferous Plug, Kersewell Quarry, Lanarkshire. *Geol. Surv. Gt. Britain, Summ. Prog.*, 1929, pt. I, p. 97. *An.* B. E. Dixon.

P. Analcite-basanite. River Ayr, 1 mile east of Stair, Ayrshire. G. W. Tyrrell, *Trans. Geol. Soc. Glasgow*, **18**, 1928, p. 273. *An.* W. H. Herdsman.

Q. Analcite-basalt (Hillhouse Type), Calton Hill, Derbyshire. S. I. Tomkeieff, *Quart. Journ. Geol. Soc.*, 1928, p. 709. **84**, *An.* S. I. Tomkeieff.

The South Kivu lavas constitute a composite province of peculiar character. Ordinary basalts of tholeiitic types are associated with essexite-basalt and soda-trachytes; an assemblage which is also found in many parts of Eastern Africa, from Abyssinia to Mozambique (Holmes, *Quart. Journ. Geol. Soc.*, **72**, 1917, pp. 260–4), and also in Madagascar, the Midland

Valley of Scotland (Tomkeieff, *Bull. Volc.*, sér. ii, **1**, 1937, pp. 59–87), and the Newer Volcanic Series of Victoria (Edwards, *Quart. Journ. Geol. Soc.*, **94**, 1937, pp 243–320). It represents in an exaggerated way an assemblage akin to that of the tholeiitic and olivine-basaltic magma types of the Brito-Arctic Tertiary

TABLE VII

	R	S	T	U	V	W
SiO_2	43·56	44·42	44·88	46·71	47·67	48·62
Al_2O_3	15·04	14·27	14·22	12·46	14·20	17·44
Fe_2O_3	2·74	3·39	1·88	3·00	3·59	5·42
FeO	8·84	8·68	9·96	9·03	9·18	6·55
MgO	8·01	7·23	7·59	9·56	6·24	5·30
CaO	10·95	12·36	10·65	11·61	8·98	10·00
Na_2O	3·28	3·64	2·85	3·10	3·21	2·30
K_2O	·92	2·44	3·09	1·06	2·41	1·92
$H_2O +$	1·82	·15	·08	1·11	·92	·63
$H_2O -$	·84	·09	·03			
CO_2	none	—	·06	—	—	—
TiO_2	2·82	3·42	3·40	1·74	2·64	1·29
P_2O_5	·79	·13	·62	·33	·66	·11
MnO	·23	—	·19	—	—	·21
Incl.	—	—	·15	·05	·10	—
	99·84	100·17	99·65	99·76	99·80	99·79

R. Essexite-basalt, B. 246, south of Kahusi, South Kivu Volcanic Field. *An.* W. H. Herdsman.

S. Basanitoid. Glassy lava of 1912 eruption of Rumoka (formerly known as the Katerusi lava), north of Lake Kivu. A Lacroix, *Min. de Madagascar*, iii, 1923, 265. *An.* F. Raoult.

T. Leucite-basanite. Stated to be from the 1905 lava of Kanamaharagi, east of Nyamlagira, but probably representing the lava erupted about 1901 from Singiro, on the south-east slope of Nyamlagira (private communication from A. D. Combe). N. L. Bowen, 1938, p. 27. *An.* R. B. Ellestad.

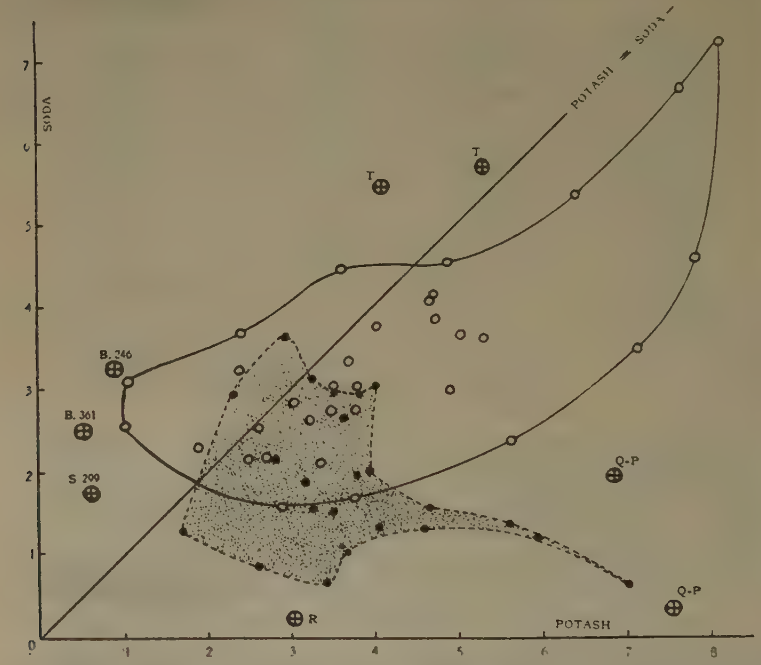
U. Basanitoid limburgite, lava of 1904–5 eruption of Nahimbi (formerly known as the Adolf Friedrich Volcano), north of Lake Kivu. L. Finckh, 1912, p. 22. *An.* O. Hauser.

V. Doleritic leucite-basanite (Leucite-trachybasalt), Mukira, north of Lake Kivu. *Ibid.*, p. 18. *An.* O. Hauser.

W. Trachydoleritic leucite-basanite (Leucitic trachybasalt), near Kisenye, north shore of Lake Kivu. *Ibid.*, p. 18. *An.* O. Hauser.

province, and, like the latter, it presents a petrological problem that has not yet been adequately solved. Bowen's suggestion (1938, p. 32) "that the old sodic trachytes of South Kivu, and the associated trachy-dolerites, are representative of the original characters of the early magmas" cannot be accepted—especially as it refers to the magmas of North as well as South Kivu—in view of the facts: (*a*) that the oldest lavas of South Kivu include basalts that are particularly poor in alkalies; (*b*) that some of the later basalts are normal tholeiitic types; and (*c*) that the earliest products of many of the centres of activity north of Lake Kivu are potassic rocks, such as biotite-pyroxenite and katungite (Holmes, 1937).

Moreover, the South Kivu field differs from all the provinces referred to above in virtue of the occurrence there of highly potassic acid rocks. Sorotchinsky (1934) interprets the latter as fusion products of correspondingly potassic crustal rocks. Commenting on this hypothesis, I pointed out that "in all the other examples of transfusion or palingenesis which have been investigated chemically noteworthy changes in composition are shown to have been involved" (Holmes and Harwood, 1937, p. 275), and suggested "that some of the acid lavas may also have required the co-operation of potash-rich emanations". Professor Thoreau, who has examined the specimens, tells me



Text-fig. 2.—Diagram illustrating the distribution of alkalies in the analysed volcanic rocks of the Western Rift. *Toro-Ankole* province, black dots in shaded field; *Birunga* province (including Bufumbira), open circles in field outlined by a continuous line; *South Kivu* province, crosses in circles. The analysed basaltic rocks discussed in the text are S. 299, B. 361, and B. 246. T = trachyte, R = rhyolite, Q-P = quartz-porphyry.

that he thinks they are hydrothermally altered, a view that is shared, on theoretical grounds, by Bowen (1938, p. 32). Whether the high potash is an inherited character from pre-existing crustal rocks or a secondary acquisition from later emanations, the fact remains that in the South Kivu field the trend of alkali change was from sodic to potassic, whereas in the provinces to the north the trend has been, and still is, from potassic to sodic.

In conclusion, grateful acknowledgment is made to Professor J. Thoreau for the gift of the specimens which have been analysed, and to the Grants Committee of the Royal Society for a grant, out of which the cost of the analyses has been defrayed.

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Montmorillonite in Fuller's Earth, Nutfield, Surrey

By A. Brammall and J. G. C. Leech, in collaboration
with W. J. Dunstall

I. Introduction

THE petrography and stratigraphical setting of the Nutfield fuller's earths were recently described by E. F. Newton (1) who also made a complete study of the accessory minerals associated with the actual "fuller's earth material", which is the main constituent of the native earths processed at Redhill, Surrey.

Preliminary tests made on both the processed and native earths revealed the high base-exchange capacity characteristic of the bentonite clays. A provisional identification of the main constituent, as a member of the montmorillonite group, was confirmed by X-ray diffraction data kindly determined by Dr. G. Nagelschmidt, Rothamsted Experimental Station.

II. Laboratory Investigation

The fractionation of clays is a difficulty familiar to all workers in clay-chemistry. Even the finest suspensoids are liable to contain more than one specific clay-mineral, together with the hydrogels of silica, alumina, and ferric oxide, and to entangle particles of such minerals as calcite, quartz, felspar, mica, etc.

The validity of a specific formula computed from the analysis of a clay-fraction must depend on the accuracy of allowances made for contaminants.

In the Nutfield earths, the chief contaminant is essentially pure calcite, which accounts for 3–20 per cent of the clay-fractions separated by the method described below. The remaining aliens comprise the species listed in Table II.

(*a*) *Fractionation.*—Lump samples taken from the main seam at the Cockley pit were allowed to disintegrate to coarse "crumb" by exposure to the laboratory atmosphere for about a fortnight. This air-dried "crumb" was next powdered, and quartered down to about 3 kilograms, which served as the stock sample.

Successive portions (50 gm.) of this sample were deflocculated in a glass tank (45 × 30 × 20 cm.) containing ammoniacal tap-water—stirred vigorously at intervals during the first day's treatment. Sedimentation was allowed to proceed overnight (for about 17 hours).

Thereafter, the upper 20 cm. or so of cloudy liquid were siphoned into 2-litre glass jars, and the suspensoid fraction ($< 5\mu$) was slowly precipitated by adding to the liquid two or three small crystals of calcium chloride.

The coagulum was then separated on a Buchner pressure-filter (using a toughened No. 50 paper), and thoroughly washed, on the filter, with approximately neutral (*p*H 7) distilled water until the filtrate was free from chloride, sulphate, calcium, and magnesium. The air-dried solid was a pale-buff powder with a faint greenish shade. Determinative work was done on this powder.

(*b*) *Mineralogy of the Clay-fraction.*—The main constituent is montmorillonite (76–90 per cent). No appreciable trace of sericite, or kaolinite, could be detected in X-ray powder-photographs. The alien minerals identified are briefly mentioned below.

Montmorillonite is a soft, flaky, mica-like substance. In form and habit it resembles kaolinite; but its constitution is more complex than that of kaolinite, and its composition is very variable (2). For fraction V, Table 1, the Ref. Index is 1·493 ± ·002, the birefringence, ·001 – ·002.

Viewed at high magnification, dispersed flakes of the Nutfield variety are colourless—though patchily stained with film of hydrated ferric oxide, to which the buff-colour of the clay-fraction is due. They are also, habitually, dappled with pin-point specks of mineral-inclusions identifiable (at × 800 or higher magnification) as sphene, calcite, barytes, etc., which occur also as discrete particles. These alien minerals are "computed out" from bulk analyses to arrive at the net montmorillonite-composition (Table III).

Free silica comprises both the crystalline (quartz) and amorphous (opaline) forms. Exact assessment of the two still presents serious difficulties.

In the Nutfield earths, quartz is uncommon, capriciously distributed, and coarse enough to be essentially eliminated from clay-fractions separated by the method described above. Though its complete elimination cannot be assumed, the amount present in the fractions analysed is doubtless much too small to invalidate the net montmorillonite-composition computed (Table III).

Amorphous silica is known to be present—in small, yet significant amounts, even in fractions below the 1μ grade. It is attributed,

TABLE I

ANALYSES OF NUTFIELD FULLER'S EARTHS, CLAY-FRACTIONS, AND B.E. DERIVATIVES.

	I	II	III	IV	V	VI	VII	VIII
SiO_2 . .	56·89	49·01	42·46	48·94	42·04	41·89	42·02	49·26
Al_2O_3 . .	15·11	13·18	12·44	13·02	11·79	11·64	11·40	14·08
Fe_2O_3 . .	5·80	4·57	3·96	4·88	4·06	3·91	4·09	3·47
FeO . .	·83	1·50	·79	·79	1·05	1·09	1·07	1·68
MgO . .	3·13	3·10	3·06	5·84	2·80	3·76	2·85	2·99
MnO . .	·01	n.d.	nil	nil	·01	·01	·01	tr.
CaO . .	4·27	5·84	10·45	3·02	13·33	11·84	13·24	2·12
Na_2O . .	·30	·10	tr.	·04	·06	·15	·09	·19
K_2O . .	·74	·31	·04	·13	·24	·29	·24	·51
TiO_2 . .	·66	·66	·37	·66	·50	·49	·50	·56
CO_2 . .	1·20	2·16	5·88	1·64	8·58	8·35	8·54	·12
P_2O_5 .	·10	·09	·06	·10	·09	·09	·11	·05
BaO . .	·12	n.d.	n.d.	n.d.	·07	·07	·07	n.d.
* H_2O (+) .	6·23	6·51	7·04	6·96	4·86	5·51	4·79	5·06
* H_2O (−) .	4·79	11·72	13·63	14·04	10·55	10·86	11·20	19·30
F . .	·08	—	—	—	—	—	—	Cl ·18
	100·26	98·65	100·18	100·06	100·03	99·95	100·23	99·97
Exchangeable bases (calc'd):								
CaO . .	2·07	2·48	2·62	·32	1·93	·67	1·80	—
MgO . .	·22	·16	·14	2·12	·33	1·25	·35	—
B.E. capacity: At H_2O% found .	82† 86	97	98	116	84	86	80	78† 88

* H_2O% above, and below, 105° C., No. VIII excepted, for which the datum is 300° C.

Base-exchange capacity : † actually determined ; the rest, computed.

Analysts : Geochemical Laboratories, London, Nos. I and VIII ; W. J. Dunstall, Imperial College, London, Nos. II, V–VII ; W. H. Herdsman, Nos. III and IV.

Base-exchange determinations : I, by Geochemical Laboratories ; VIII, by Dr. R. K. Schofield, Rothamsted Experimental Station, Harpenden.

I. Native earth, after being processed (Fuller's Earth Union, Copyhold Works, Redhill, Surrey).

II. Clay-fraction (< 5μ) elutriated from I.

III. Clay-fraction (< 5μ) of a " native earth " sample.

IV. Fraction III, after partial base-exchange with N/$MgCl_2$-solution (in " closed " system).

V. Clay-fraction (< 5μ) of another " native earth " sample.

VI. Fraction V, after partial base-exchange with N/$MgCl_2$-solution (in " closed " system).

VII. Product VI, after treatment (in " closed " system) with N/$CaCl_2$-solution to restore calcium discharged by previous treatment.

VIII. Fraction V, after extraction with N/20 HCl-solution and subsequent conversion of the H-clay to the saturated Ca-clay.

mainly if not entirely, to the minute opaline sponge-spicules described by Newton (loc. cit.).

No technique hitherto proposed for the quantitative estimation of free silica in clay-fractions can give entirely unequivocal results. The same observation applies also to the hydrogels of alumina and ferric oxide. The various alternative methods having been considered (and tested), tentative assessments (by W. J. Dunstall) have been adopted as follows :—

(i) *Free Silica and Free Alumina* : the amounts extracted by cold N/NaOH-solution in four hours, though the bulk of the available solute appears to be extracted in the first two hours.

(ii) *Free Ferric Oxide* : the amount extracted by cold 5 per cent $NaHSO_3$-solution in 30 minutes.

TABLE II

MINERAL COMPOSITION OF NUTFIELD FULLER'S EARTH AND CLAY-FRACTIONS.

	Works product :		Native earths :	
Ref. : Table I	Sample I	Clay-fraction II	Clay-fractions III	IV
Montmorillonite . .	85·2	90·0	84·1	76·0
Calcite	2·7	4·9	13·4	19·5
Felspar	7·2	2·8	·28	1·9
Sphene	1·6	1·6	·9	1·2
Apatite	·23	·2	·13	·2
Barytes	·19	·1	·1	·11
Quartz	·8	tr.	tr.	tr.
Hydrated silica . .	1·30	about the same.	·73	·66
„ alumina . .	·20		·04	·04
„ ferric oxide . .	·50		·41	·37
„ manganese oxides.	·01		nil	·01
Zinc blende and galena with pyrite.	·10	tr.	tr.	tr.

Sphene accounts for probably the whole of the TiO_2 content shown in the analyses. Neither sphene, nor any of the associated aliens, can be completely eliminated by centrifugation in heavy liquids ; in any case, the use of organic liquids in the manipulation of clays intended for base-exchange tests is inadvisable.

Felspars in the Nutfield earths are demonstrably authigenic. Newton's data indicate a variety of anorthoclase unusually rich in lime. But the felspar crop proves to be heterogeneous, and the average composition is variable. For the purpose in view, the estimation of felspar (for elimination from analyses) presented an important though minor problem :

As the small percentages of potash and soda shown in the analyses remain essentially " fixed " under base-exchange conditions (Table I), and as sericite is essentially absent, the two alkalies may safely be regarded as " fixed " in felspar. The amount of lime combined in this felspar has been standardized at $\frac{1}{10}$ the equivalent of the total alkalies.

Barytes, Manganese Oxides, and Sulphides : the former occurs in significant amount ; the remaining two are quite negligible. By appropriate deductions from bulk analyses (Table I), these alien species are allowed for (Table II) and the net montmorillonite composition is computed (Table III).

III. THE MONTMORILLONITE-CONSTITUTION, IN RELATION TO BASE-EXCHANGE.

Base-exchange claims a copious literature ; but the various interpretations of base-exchange mechanism, to 1930 at least, have come under critical review as the result of X-ray work (2, 3, 4, 5).

Chemical and X-ray data relevant to the base-exchange clays, and to montmorillonite in particular, have recently been reviewed, in the light of new facts, by Dr. G. Nagelschmidt (2), who shows that, while several minor problems await the results of investigations in progress, facts already established warrant the tentative treatment first outlined by Marshall (3), and set out below.

The montmorillonite-constitution is probably closely related to that of pyrophyllite, in which the sequence of atomic planes along a direction perpendicular to these planes is :—

$$\begin{array}{l} O_6 \\ Si_4 \\ O_4(OH)_2 \\ Al_4 \\ O_4(OH)_2 \\ Si_4 \\ O_6 \end{array} \quad \text{conveniently assembled :} \quad \left.\begin{array}{r} \text{Si-layer}\lbrace\ Si_4 \\ \text{Al-layer}\lbrace\ Al_4 \\ \text{Si-layer}\lbrace\ Si_4 \end{array}\right\rbrace O_{20}(OH)_4$$

$$\text{Charges :}\ \overset{+}{44} \qquad \overset{-}{44}$$

Base-exchange capacity (which pyrophyllite lacks) is in some way related to atomic replacements in these three layers :—

(i) In the Si-layers : Si-atoms are replaced by Al-atoms.

(ii) In the Al-layers : Al-atoms are replaced by Mg, Fe'', Mn ; or by Fe''' ; or, to a small extent, Ti, and occasionally Li.

Each replacement disturbs the balance between the positive and negative charges on the lattice as a whole. For example :

if one Si-atom is replaced by one Al-atom, or (in the middle layer) one Al-atom is replaced by one Mg-atom, one unit of surplus negative charge arises on the layer concerned.

Cancellation of this surplus negative charge is provisionally assumed to be effected by the attachment of surplus (exchangeable) kations—chiefly Ca (as in the Nutfield earths), or Mg, K, Na, singly or together (as in the varieties recorded by Dr. Nagelschmidt, Table III).

In montmorillonite, replacement affects the Si-layers mainly; in beidellite, the middle layer is the main locus of replacement.

The bentonite-constitution may now be generalized, thus:—

$$R'_n = (\mathrm{Mg\ Fe''})\ \text{atoms}\ \begin{matrix} R'_m \\ \\ R'_m \end{matrix}\left[\begin{matrix} \mathrm{Si}_{4-m}\mathrm{Al}_m \\ \mathrm{Al}_{4-p}\,(\mathrm{Mg\ Fe''\ Fe'''}\ \ldots)_p \\ \mathrm{Si}_{4-m}\mathrm{Al}_m \end{matrix}\right]\mathrm{O}_{20}(\mathrm{OH})_4$$

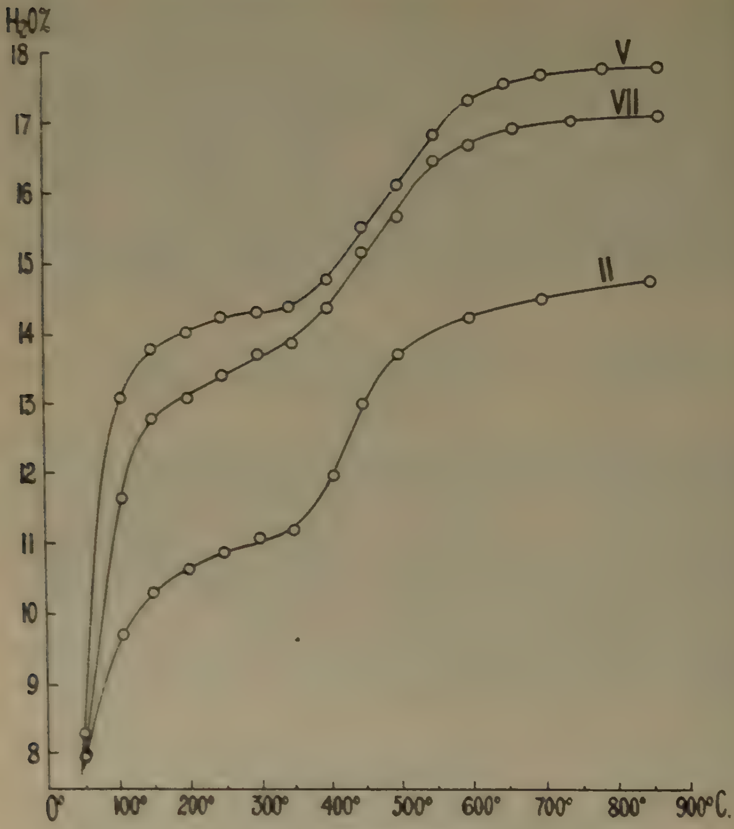
This formulation, of course, assumes constancy for the group $O_{20}(OH)_4$ which, however, may prove to be variable (6). The four hydroxyls correspond to about 5 per cent water. At 50 per cent humidity, montmorillonite appears to adsorb another 10–13 per cent of water the bulk of which, for the present, is regarded as eliminated below 105° C.

The general interpretation of the water-content is supported by the dehydration-data (and curves, Fig. 1) for the three clay-fractions II, V, and VII, Table 1:

DEHYDRATION DATA

II		V		VII	
Temp.	*H_2O loss, per cent.*	*Temp.*	*H_2O loss, per cent.*	*Temp.*	*H_2O loss, per cent.*
50°	7·93	50°	8·29	50°	7·99
105°	9·68	105°	13·08	105°	11·63
150°	10·29	150°	13·75	150°	12·75
200°	10·62	200°	14·00	200°	13·06
250°	10·85	250°	14·22	250°	13·37
300°	11·04	300°	14·28	300°	13·66
350°	11·16	345°	14·34	350°	13·80
405°	11·92	400°	14·74	400°	14·34
450°	12·94	450°	15·57	450°	15·11
500°	13·65	500°	16·05	500°	15·62
600°	14·19	550°	16·76	550°	16·39
700°	14·43	600°	17·23	600°	16·62
850°	14·66	650°	17·48	660°	16·84
		700°	17·59	740°	16·92
		780°	17·66	860°	16·96
		860°	17·64		

Dehydration data determined by W. J. Dunstall.



TEXT-FIG. 1.—Dehydration Curves.

IV. COMPUTATION OF THE BENTONITE CONSTITUTION

The method of computation is briefly outlined in the following tabulation :—

Example : Analysis I, Table III.

	Per cent.	*Mol. proportions.*	*Atoms.*
SiO_2	53·32	0·888	·888
Al_2O_3	14·50	0·142	·284
Fe_2O_3	5·70	·036	·072
FeO	·89	·012	·012
MgO	3·36	·081	·081
CaO	2·23	·039	·039

Allotments.		
Si	·888	to Si-layers
Al	x	
Al	·284 − x	to Al-layer
Fe'''	·072	
Fe''	·012	
Mg	·081 − y	
Mg	y	Exchangeable surplus kations.
Ca	·039	

Two simple equations evaluate x and y, and the formulation is then raised to the basis (SiAl) = 8. For another mode of approach, which leads to the same result but explains (and provides for) contingencies which may arise in the general case, the reader is referred to Dr. Nagelschmidt's discussion of the montmorillonite-constitution (loc. cit.).

TABLE III

(i) CHEMICAL COMPOSITION OF NUTFIELD MONTMORILLONITES—COMPARED WITH THAT OF WELL-ESTABLISHED STANDARDS (RECORDED BY NAGELSCHMIDT)

	Nutfield clay-fractions (montmorillonite).				Recorded by G. Nagelschmidt.		
Ref.: Table I	I	II	III	V	Montmorillonite. (*a*)	Beid'te (*b*)	Beid'te (*c*)
SiO_2 . .	53·32	52·99	51·90	52·49	51·27	47·08	46·90
Al_2O_3 .	14·50	14·34	15·52	15·01	23·55	28·92	20·11
Fe_2O_3 .	5·70	4·63	4·45	4·87	·45	·73	8·61
FeO . .	·89	1·70	·98	1·38	—	—	—
MgO . .	3·36	3·51	3·85	3·69	2·22	·17	·69
CaO . .	2·23	2·81	3·30	2·56	2·03	2·86	2·72
Na_2O .	nil	nil	nil	nil	·47	·10	·96
K_2O . .	nil	nil	nil	nil	tr.	·12	tr.
H_2O . .	20·00	20·00	20·00	20·00	20·00	20·00	20·00
	100·00	99·98	100·00	100·00	99·99	99·98	99·99
B.E. capacity	88	107	122	109	107	120	113

(ii) ATOMIC CONSTITUTION

Si . .	7·99	7·97	7·80	7·89	7·48	6·92	7·16
Al . .	·01	·03	·20	·11	·52	1·08	·84
Al . .	2·55	2·51	2·55	2·55	3·54	3·92	2·78
Fe''' . .	·64	·52	·50	·55	·06	·08	1·00
Fe'' . .	·11	·21	·12	·17	—	—	—
Mg . .	·70	·75	·82	·73	·40	—	·16
Ca . .	—	—	—	—	—	—	·06
Mg . .	·05	·04	·04	·10	·08	·04	—
Ca . .	·36	·45	·53	·41	·32	·46	·38
Na . .	—	—	—	—	·14	·04	·28
K . .	—	—	—	—	—	·02	—
O . .	20·00	20·00	20·00	20·00	20·00	20·00	20·00
(OH) . .	4·00	4·00	4·00	4·00	4·00	4·00	4·00

V. BASE-EXCHANGE CAPACITY

Base-exchange capacity is usually expressed as the total quantity, in milliequivalents, of exchangeable kations per 100 gm. of air-dried material.

It is determinable by several alternative methods, most of which require, as a preliminary step, the conversion of the more or less saturated natural clay to H-clay (notoriously unstable) by appropriate acid treatment or by electrodialysis. Doubtless this step is necessary if, as in the Nutfield case, the clay contains an appreciable amount of calcite. It does not necessarily reflect the base-exchange conditions to which sedimentary formations are ordinarily exposed in their natural environments.

Workers in clay-chemistry consider that N/20 HCl-solution is " mild " enough to eliminate calcite and to hydrogenate the clay without damaging the finest suspensoid. The following experimental data for a test-case (by W. J. Dunstall) show that material other than calcite is certainly removed in solution :—

Twelve grammes of clay-fraction No. V (Table I) were shaken with 2 litres of N/20 HCl-solution for about two days.

The clear extract was decanted off to pass a No. 50 toughened filter-paper. This process was carried out several times—until the filtrate gave a negative test for calcium.

The 9 litres of extract were then evaporated, and the solid residue was analysed, with the following result :—

	Percentage of original material.
SiO_2 . . .	2·18
Al_2O_3 . . .	·49
Fe_2O_3 . . .	·69
MgO . . .	·20
CaO . . .	13·14
TiO_2 . . .	·004

At the conclusion of the experiment, the glass-ware surfaces were perceptibly slimy, and it seems highly probable that hydrogels were lost by deposition on the walls of flasks and funnels and probably also in the filter-paper mesh.

The H-clay thus obtained was then used as the initial material in a base-exchange determination kindly undertaken by Dr. R. K. Schofield (Rothamsted Experimental Station), who returned the balance to us in the form of the Ca-saturated clay, which was analysed—with results shown in Table I (No. VIII). These results are best examined by comparing the computed constitutional formulae for the clay-fraction in (*a*) its original, and (*b*) its final form—Ca-saturated in each case :—

	Original form.	*Final form.*
Si	7·89	7·99
Al	·11	·01
Al	2·55	2·73
Fe‴	·55	·41
Fe″	·17	·25
Mg	·73	·61
Mg	·10	·18
Ca	·41	·25

Commenting on the observed discordances and on the composition of the acid-soluble fraction—Si : (AlFe‴) : (MgFe″Ca) $= 8 : 4 : > 1$, Dr. Schofield considers that, though the acid washing did, in fact, remove (besides calcite) something which might, fairly, be called montmorillonite, this acid-soluble material differed from the residue, which is, therefore, more homogeneous than the original material. The acid-soluble fraction appears to be differentiated from the more refractory residue by being richer in magnesia and iron, poorer in alumina.

If this be the case, the Nutfield fuller's earths betray an early stage of reconstitution—the partition of the original clay-system by a differentiation process which is metamorphic in kind, yet operative within the mass of an unconsolidated sediment. Evolutes of such fuller's earth deposits (shales, slates, and phyllites for example), have still to be recognized.

V. ALKALI-POOR BENTONITE IN REGIONAL METAMORPHISM : A SUGGESTION

In bulk-composition, the Nutfield fuller's earths differ from the " average shale " computed by Daly in being alkali-poor—total alkalies being only about 1 per cent, or less, in contrast with 4–6 per cent in " av. shale ".

Viewed as an " initial pelite system ", it is shifted from the more normal locus (near the sericite-chlorite or muscovite-biotite poles) towards staurolite and its isograd kyanite (7).

The ideal staurolite-composition indicated by X-ray analysis (5, p. 170) is $H_2FeSi_2Al_4O_{12}$; the structure is, in fact, composed of alternate layers of kyanite and $Fe(OH)_2$ grading probably towards $Mg(OH)_2$. Kyanite, as a separate phase, may be regarded as " excess " over requirements for staurolite. If staurolite is to be initiated, the two components Al_2SiO_5 and $Fe(OH)_2$ must attain reactivity and competent concentration, and continued growth would be opposed by the counter-claims of K-ions in favour of muscovite (at the expense of kyanite) and biotite (at the expense of both kyanite and $Fe(OH)_2$). In the bentonite system presumed, inhibition due to K-ions should be small. In the general case, the association of the two micas with staurolite is to be expected and is, in fact, common.

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The Petrology of the Government Reserve Forest, Kodarma, Bihar (India)

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I. INTRODUCTION AND PREVIOUS LITERATURE

KODARMA is one of the most important centres for the production of muscovite mica in the mica-belt of the Hazaribagh district of Bihar. The Kodarma Reserve Forest, the petrology of which is here described, begins about 2 miles north-east of Kodarma Station and extends for a further distance of about 10 miles in that direction. It occupies an area of about 57 square miles.

Though the Kodarma area, on account of its mica production, had attracted the attention of geologists and mining engineers even at the beginning of last century, very little is known about the rocks of the area. Medlicott (1) and Mallet (2) made reference to the granite-gneiss (" Dome-gneiss ") and the mica-schists of this belt of Bihar. The Archaean rocks of India were subdivided at that time into " Gneiss or Metamorphic " and " Transition or Submetamorphic " (3). The " Submetamorphic Series " included the older unfossiliferous formations occupying positions intermediate between the rocks of the Vindhyan system and the gneisses and granites of the " Metamorphic Series ". Medlicott regarded the dome-gneiss as younger than and intrusive into the mica-schists, whereas Mallet thought it belonged to the " Metamorphic Series " and was older than the mica-schists which he considered to belong to the " Submetamorphic Series ".

In his memoir on the mica deposits of India, Sir Thomas Holland (4) supported Medlicott's view and suggested that the dome-gneiss of Kodarma is a granite intrusive into mica-schists and other country-rocks, and that the mica-pegmatites are genetically connected with the dome-gneiss. Professor S. K. Roy and Mr. N. C. Nandy (5) gave further proofs of the intrusive relation of the dome-gneiss with the country-rocks but, unlike Holland, they regarded the dome-gneiss as regionally metamorphosed granite.

In addition to these references, there have appeared several papers on the mica deposits. A discussion of the origin of the mica-pegmatites, complete with references to previous work thereon, has been recently given by S. K. Roy, N. L. Sharma, and G. C. Chattopadhyay (6). The present author (7) has described the felspars of the mica-pegmatites.

The main rocks of the Kodarma Reserve Forest may be classified in the following divisions arranged in a time sequence :

6. Dolerite	Post-Gondwana (Jurassic or Tertiary?).
5. Meta-dolerite . .	Post Dharwar (Cuddapah or earlier).
4. Pegmatites.	Post Dharwar (Pre-Cuddapah).
3. Dome-gneiss (Granite-gneiss)	
2. Epidiorites (Amphibolites) .	. . Upper Dharwar.
1. Sillimanite-gneisses, mica-gneisses and schists, calc-silicate-granulites	Lower Dharwar.

The dome-gneiss had been regarded by previous workers as of purely igneous origin, but the present author now suggests that some of it is mixed gneiss of composite character. The examination of the country-rocks, furthermore, has strengthened the injection-complex suggestion. The sillimanite-gneiss is more common in this area than has been supposed so far, and many of the so-called "mica-schists" are felspathized with oligoclase. The calc-silicate-granulites were originally all regarded as ortho-rocks, but most of them now prove to be of sedimentary origin.

In this paper, the basic rocks, though described in the sequel under one heading, have been systematically classified and correlated with those of other areas. The amphibolite bands, hitherto considered to be dykes passing through the dome-gneiss, are now interpreted as disrupted portions of pre-existing basic masses which have resisted injection and assimilation by the granite magma, whereas the other country-rocks have yielded to the injection.

II. THE METAMORPHOSED SEDIMENTARY ROCKS

The para-metamorphosed country-rocks in the Kodarma Reserve Forest may be grouped under the following headings :—

(i) Sillimanite-gneisses, (ii) muscovite- and biotite-gneisses, (iii) muscovite-biotite-schists, (iv) calc-silicate-granulites.

No stratigraphical sequence has so far been established amongst these rocks. The gneisses described under sillimanite-gneisses are only those which have sillimanite as one of their important constituents. With the absence of sillimanite, sillimanite-gneisses pass into gneisses of the second group which themselves, with the almost complete absence of felspar and an abundance of muscovite, pass into muscovite-biotite-schists of the third group. It seems that the various micaceous country-rocks represent the products of metamorphism, including injection by magmatic juices, of a series of sediments pelitic and semi-pelitic in nature. The calc-silicate granulites are of very subordinate importance in this area. They most likely represent metamorphosed bands of impure calcareous sediments.

(i) *Sillimanite-Gneisses.*

In hand-specimens, these gneisses are characterized by their foliated, almost schistose, nature due to the planar arrangement of micas and alternating thin lenticular felspathic patches. Some of the sillimanite-gneisses, especially those from near pegmatites, show augen structure and consist of strongly foliated thin micaceous layers with fibrolite, alternating with thick lenticular bands of quartz and felspar. These bands enclose augen, 2 in. by 1 in. in size, of plagioclase of the same composition as that of the bands. Isolated grains of brownish-red garnet are sometimes observed in the micaceous as well as in the felspathic portions. In some specimens sillimanite can be seen as white or bluish-grey elongated fibrous patches.

The sillimanite-gneisses are essentially composed of biotite, muscovite, quartz, felspar, and sillimanite; apatite, zircon, magnetite, tourmaline, and garnet are the important accessories; chlorite, zeolites, and limonite are secondary late introductions. They may be divided into two types according to their dominant felspar—sillimanite-microcline-gneisses, sillimanite-plagioclase-gneisses.

The biotite of the microcline-bearing sillimanite-gneisses is a strongly pleochroic reddish-brown type, whereas that of the plagioclase-bearing variety has a greenish tinge, its pleochroism being X = pale greenish or yellowish brown, Y = Z = dark greenish brown. Basal flakes of biotite often show inclusions lighter in colour than the host—these probably represent the earliest stage of the alteration of biotite to fibrolite. The biotite of the felspathic bands occurs as clear flakes with smooth boundary and is free from sillimanite needles. This may be recrystallized biotite, as it has been observed that the biotite in the micaceous fibrolite-bearing bands is usually full of a network of fibres of sillimanite.

Muscovite flakes often lie across the alignment of biotite flakes, and sometimes the continuation of the biotite-cleavage can be seen in the enclosed muscovite. In one specimen, a slightly curved but long idiomorphic flake of muscovite is seen to cut across several flakes of biotite and to pass into the adjacent felspar. These observations, and others, suggest that though most of the muscovite may have originated simultaneously with biotite, some of it, which is better crystallized, has been formed later than the biotite and has replaced it.

Sillimanite occurs as fine needles included in biotite, muscovite, and quartz. As the number of needles increases in biotite, the latter becomes bleached and a dirty grey fibrous aggregate results with usually slightly lower refringence than that of the clear prismatic sillimanite. Sometimes felts of grey fibrolite pass into thin prisms of colourless sillimanite elongated along the same direction. In some specimens, however, some of the colourless sillimanite occurs in idioblastic crystals arranged linearly across the direction of foliation in the rock. It is, therefore, possible that while most of the sillimanite, especially fibrolite, might have been derived directly from biotite, some which is idioblastic in habit and transects the foliation may have crystallized at a later stage. The later period of crystallization of this mineral compared to the other constituents is also shown by the occurrence of veinlets of fibrolite in fresh felspar and by arc-shaped strings of sillimanite in quartz.

Quartz and felspars form the groundmass which varies greatly in grain-size at different places in the same slide. The components of the felspathic bands are very coarsely crystallized. In the microcline-bearing gneisses, the bigger plates of microcline sometimes contain innumerable inclusions of quartz grains. Microcline shows only incipient twinning and perthitic stringers. The plagioclase, a basic oligoclase or more rarely andesine, forms large plates.

Zircon, colourless or brown, is a common accessory as small rounded or long irregular grains. Tourmaline, pleochroic from pale green to brownish green, occurs as a few subhedral crystals. Apatite is an important accessory in some sections. Magnetite occurs as irregular grains. Garnet has been seen in only a few specimens, where it forms rounded porphyroblasts showing cracks filled with limonite or chlorite. Fine veins of limonite and chloritic material traverse the other minerals of these rocks.

The sillimanite-gneisses may be taken to be simply regionally metamorphosed pelitic sediments, but the occurrence of abundant oligoclase felspar especially in augen form suggests that injection-processes must also have taken a considerable part in their formation. Most of the augen-specimens come from near the contact of mica-pegmatites, and it is thought that metasomatic action has taken place.

In the sillimanite-gneisses it has been observed that the microcline-bearing variety usually contains reddish-brown biotite and shows typical metamorphic texture when we consider its quartzo-felspathic groundmass; on the other hand, the oligoclase-bearing variety, which contains greenish-brown biotite, often shows coarsely crystallized granoblastic texture and sometimes augen-structure. Both types of biotite are also found in the dome-gneiss, as mentioned below, but the reddish-brown biotite is more common in the "biotite-rich granite-gneiss" variety of dome-gneiss. Specimens of sillimanite-gneiss containing greenish-brown biotite usually come from near the contacts with pegmatites, and it is possible that the pegmatitic juices are partly responsible for a change of reddish-brown biotite to the greenish-brown variety.

The abundance of microcline, often porphyroblastic or poikiloblastic in texture, in some of the sillimanite-gneisses is considered to be the result of permeation by potash solutions. This permeation was followed later by injection with soda solutions, the work of which is manifest in the augen of oligoclase. The presence of tourmaline indicates, also, the activity of other fluid agents.

In part, the change of biotite to sillimanite seems to represent a late phase in the metamorphism of these rocks, since veinlets of fibrolite inject all the essential minerals. The coarser grain of these sillimanite-plagioclase-gneisses and the association of more clear sillimanite prisms with fibrolite show that the addition of soda solutions increased mobility in the rocks and permitted free movements of mineral molecules and the generation of bigger crystals. The arrangement of better crystallized and thicker prisms of sillimanite across the foliation-direction of fibrolite and biotite points to two generations of the aluminium silicate.

(ii) *Muscovite- and Biotite-Gneisses.*

This group is very variable in texture, structure, and proportions of its mineral constituents. Both muscovite and biotite are present in all, but the mutual proportions vary, giving rise to muscovite-gneisses and biotite-gneisses. Specimens from the neighbourhood of mica-pegmatite intrusions are generally coarsely crystallized and often show red garnets up to half an inch in diameter, together with green apatite and black tourmaline.

These rocks are essentially composed of biotite, muscovite, quartz, and felspar. The muscovite-rich gneisses usually contain an acid oligoclase and rarely microcline, whereas the biotite-rich varieties have a basic oligoclase of composition $Ab_{80}An_{20}$ to $Ab_{70}An_{30}$. Quartz usually shows undulose extinction and strain phenomena. Biotite is generally of the reddish-brown type, but greenish-brown biotite is also observed especially in coarsely crystallized varieties. In some specimens collected from the contact with mica-pegmatites, muscovite is seen to replace biotite and in turn to be replaced by oligoclase ; in these, graphic and myrmekite-like intergrowths of quartz are observed both in oligoclase and muscovite. It is inferred that such structures are due to the replacement of oligoclase and muscovite by quartz-bearing pegmatitic solutions.

Tourmaline is a common accessory, in prismatic subhedra, pleochroic from colourless to bluish-brown or from pale yellow to patchy brown. Zircon is rare as inclusions in muscovite. Apatite occurs in thick prismatic subhedra or as rounded grains. Magnetite is usually associated with biotite. Garnet, colourless or pinkish in section, occurs in rounded or subhedral forms.

The presence of pegmatite minerals, like oligoclase, tourmaline, garnet, and apatite, especially in specimens from near the pegmatitic veins, shows that these gneisses represent sediments of pelitic or semipelitic nature which have been permeated or metasomatically affected by the pegmatitic juices. Microcline-mica-gneisses are not common but their existence is deduced from certain rocks, " schistose muscovite-biotite-gneiss," occurring in association with the dome-gneiss which are very similar to the mica-gneisses in hand-specimens but are rich both in microcline and oligoclase. Apparently most of the potash of the injection-solutions has been used up in the formation of muscovite in the mica-gneisses.

The origin of the garnet of these rocks is a matter for discussion. In some cases, this mineral is limited to the contact-zone of the mica-pegmatites, occurring both in the contact-rocks and in the adjoining pegmatites where garnets sometimes a foot across have been found. This suggests that the garnet in the gneiss has been derived from the pegmatite magma itself and is thus of ultimate igneous parentage. A. L. Anderson (8) in his study of Idaho pegmatites came to a similar conclusion, observing a sequence of replacements, with garnet as the last term, in the contact-zone of muscovite-biotite-schist similar to that within the pegmatite. Anderson stated that the " relations suggest a large transference of soda, potash, boron, and water from the pegmatitic bodies into the enclosing rock probably by the same solutions that permeated the pegmatites themselves and caused the later replacements therein ". On the other hand, some of the garnet-rich bands in the micaceous country-rocks may have been formed by the contact-metamorphic alteration of certain iron- and aluminium-rich portions of the sedimentary rocks. Such an origin has been advocated by L. C. Conant (9) for the garnet deposits of New Hampshire where, subsequent to the formation of biotite- and sillimanite-schists, emanations from a granite batholith are considered to have converted the iron-aluminium portion of the roof into the garnet-rich rock. It is suggested, therefore, that in the mica-gneiss of the Kodarma area, it is possible that the pegmatite solutions and the material of the country-rocks have, individually and jointly, taken part in the formation of garnet.

(iii) *Muscovite-Biotite-Schists.*

These rocks differ from the mica-gneisses by the almost complete absence of felspar and by the dominance of muscovite over biotite. They vary greatly in texture. The coarsely crystallized varieties are confined to the proximity of pegmatites and are usually tourmalinized. In the finer-grained types, oriented mica plates cause the rock to break into slabs.

Muscovite, quartz, and biotite are the essential components, with accessory tourmaline, apatite, zircon, epidote, orthite, and magnetite. Muscovite shows a planar arrangement ; its cleavage cracks are widely opened and are sometimes full of minute opaque inclusions. Biotite, yellowish brown or greenish brown in colour, sometimes contains interlacing acicular crystals of tourmaline. Biotite occurs along the cleavage planes of the muscovite or in parallel intergrowth with the latter. Quartz is usually coarsely crystalline and often shows strain-phenomena. Zircon, as subhedral prisms or rounded grains, apatite in small prisms, and magnetite in irregular grains are common accessories. Colourless epidote or brownish orthite is rare. Tourmaline and garnet are found only in specimens collected from areas where pegmatites are abundant.

These mica-schists represent metamorphosed impure argillaceous sediments. The presence of tourmaline, apatite, and garnet suggests, however, that the original composition of the parent sediments has been altered by transfer of material from granitic and pegmatitic sources. For a similar reason the country-rocks of mica-pegmatites are always enriched in mica giving rise to the so-called mica-schists.

(iv) *Calc-Silicate-Granulites.*

These rocks are massive and heavy, varying in texture from fine to medium grained. They are reddish, greenish, or grey in colour and are sometimes spotted with these colours. Some of the fine-grained dark grey rocks have the appearance of impure quartzites.

According to the mineral composition, these rocks have been classified into (*a*) diopside-rock, (*b*) diopside-epidote-granulite, (*c*) diopside-epidote-garnet-granulite, (*d*) hornblende-epidote-garnet-granulite, and (*e*) epidote-garnet-granulite.

The diopside-rock is composed of a granoblastic aggregate of brownish diopside ; a few rounded sections of zoisite and angular sections of brownish sphene have been observed, while magnetite is an important accessory ; chlorite occurs as subhedral flakes.

In the diopside-epidote-granulites the constituents are plagioclase, diopside, quartz, epidote, orthite, sphene, and magnetite. The fresh plagioclase is a labradorite, approaching $Ab_{40}An_{60}$. The diopside is pleochroic with X = bluish green, Y = yellowish green, and Z = bluish green ; it is occasionally altered marginally to greenish blue hornblende. Quartz, with varying grain-size, occurs in almost equal proportions to felspar. Epidote forms subhedral crystals often with a core of yellowish or greenish orthite altered to isotropic material. Sphene occurs as small angular or rounded grains, and magnetite as rather bigger subhedral ones.

The diopside-epidote-garnet-granulites are characterized by a reddish grossularite. This mineral contains inclusions of plagioclase, diopside, and orthite, the latter occurring as a core as it does in most of the epidote sections. The garnet is sometimes seen to send out tongues into the felspar or along the junction of two felspar crystals. The plagioclase is an acid bytownite. Epidote and diopside are of normal type. Orthite occurs fairly abundantly in subhedral crystals, or as cores to epidote crystals or enclosed in garnet and diopside. Sphene is present as brownish irregular grains.

The hornblende-epidote-garnet-granulite differs from these rocks by the absence of diopside and the presence of abundant hornblende in prismatic subhedra with X = greenish yellow, Y = yellowish green, and Z = greenish blue. This rock shows a banded structure due to the alternation of felspar- and epidote-rich portions.

The epidote-garnet-granulites show epidote-rich patches or greenish veins of epidote. Garnet, epidote, quartz, and plagioclase are the main components, diopside and hornblende being absent; sphene and orthite are important accessories. Quartz is coarsely crystallized. The plagioclase is a basic labradorite, approaching $Ab_{35}An_{65}$. Epidote and garnet are closely associated and both the minerals have often the same habit. Garnet is often perforated by numerous inclusions of quartz and felspar, some of which are surrounded by epidote along the margin. Epidote often occurs in the interstitial spaces between other minerals, or sends spindle-shaped veinlets among them. Sometimes epidote forms a rim round a felspar section or dissects it into several segments. Subangular pieces of garnet are often enclosed by epidote. Stringers of epidote traverse large grains of quartz. It thus seems that epidote has not been formed as a primary mineral of metamorphism, but has separated later from solutions derived from the neighbouring portion of the same rock-mass. It has definitely replaced other minerals like felspar, garnet, and quartz.

The rocks just described come from or near the margin of the dome-gneiss intrusions in the northern part of the area. Some of the bands are totally surrounded by the dome-gneiss; others are associated with amphibolitic bands included in this. They were formerly regarded as of igneous origin, but they are now considered to be of sedimentary derivation. Their mineral composition is similar to that of the calc-silicate-granulites described by H. H. Read (10) from the Sutherland injection complex. Read regards the Sutherland rocks as derived from sediments possessing the composition of marl. The Kodarma calcareous sediments might have varied in composition from place to place so as to give rise to the different types.

The presence of a band of almost monomineralic diopside-granulite may indicate, as Read (11) has suggested for comparable occurrences in Aberdeenshire, a transfer of material, chiefly silica, from the dome-gneiss.

III. THE DOME-GNEISS AND ASSOCIATED ROCKS

The granite-gneiss of the Kodarma area has been named "dome-gneiss" by previous observers on account of its peculiar mode of weathering into dome-like hillocks. This form of weathering is, however, also characteristic of many other granites in India, for example, the post-Delhi Erinpura granite of Rajputana. It is due to exfoliation and is brought about by the combined action of rainwater in the monsoons and the diurnal differences of temperature in the dry months of the year.

The rock peels off in concentric layers and prominent rounded hillocks are formed which are usually bare of all vegetation.

The early work of Medlicott and Mallet on the dome-gneiss has already been mentioned. Sir Thomas Holland (4) regarded the rock as an intrusive granite, the changes in it being not so great as to justify the use of the term metamorphic. The rock, according to him, " resembles undoubtedly eruptive granites in the possession of autoliths, formed by local concentration of its ferro-magnesian constituents, contemporaneous coarse-grained veins, xenoliths of quartzite and a well-marked zone due to contact-action near its junction with the schists."

In a paper on the petrological classification of the dome-gneiss of Kodarma by S. K. Roy and N. C. Nandy (5) further structural evidence was given in support of the intrusive nature of this rock. They suggested that the banding and schistosity may be the result of tectonic forces active during and after the intrusion of the granite magma. Unlike Holland, they regarded the dome-gneiss as regionally metamorphosed granite. They divided it into three types (1) pink biotite-gneiss, (2) grey hornblende-gneiss, and (3) greenish epidote-gneiss. The first two types are genetically connected, and the third type is considered to be an alteration product of a basic differentiate derived in some way from the main granite-magma.

(i) *Classification of the Rock-types.*

The classification of Roy and Nandy, based on colour and ferromagnesian constituents of the rock, breaks down on detailed application. The dome-gneiss is essentially a granite-gneiss with microcline, quartz, acid oligoclase, and biotite as the main constituents, and hornblende occurring in subordinate amount. Examination shows that the masses mapped as dome-gneiss are not all of pure igneous origin, for they contain rocks which are not of granite appearance or composition. Moreover, some of the dome-gneisses are very like injection-gneisses.

The dome-gneiss and associated rocks are here described under the following grouping, which is based primarily on texture and on the nature of the ferromagnesian constituents: (*a*) granite-gneiss, (*b*) foliated granite-gneiss, (*c*) biotite-rich granite-gneiss, (*d*) epidote-bearing granitic rocks, (*e*) schistose and aplitic muscovite-biotite-gneisses, (*f*) granulitic hornblende- and biotite-gneisses, (*g*) biotite-hornblende-gneiss. There is no need to describe the pegmatites associated with the dome-gneiss as they have been dealt with by Roy, Sharma, and Chattopadhyay (6).

(*a*) *Granite-gneiss.*—These rocks are medium to coarse in grain, non-porphyritic, and pink or grey in colour. They show pink and white felspars, grey quartz, and flaky biotite, this last usually forming small clusters of flakes, some of which have a tendency to be drawn out into streaks.

The granite-gneisses consist of microcline, plagioclase, quartz, and biotite. Hornblende is a rare constituent ; the important accessories are zircon, sphene, fluorite, apatite, orthite, and ilmenite or magnetite. The texture is essentially granoblastic.

Microcline is both finely and coarsely cross-twinned, and sometimes shows perthitic films of albite with an " en echelon " arrangement. It contains small inclusions of plagioclase with crenulated margins. The plagioclase of these rocks is an acid oligoclase. It sometimes protrudes into microcline but true myrmekite has not been observed. Sometimes plagioclase shows a more acidic margin against microcline which is possibly of later generation. Quartz occurs in allotriomorphic form, and may build lenticular patches with irregular margins. In one of the finer-grained specimens, it shows a highly dentated margin with oligoclase. It has attacked from two sides and worked its way along the twin planes of the felspar, indicating replacement of oligoclase by silica. Biotite, highly pleochroic with X = yellowish brown, Y = Z = dark brown, occurs in subhedral flakes without definite orientation. Muscovite is seen sometimes with biotite, and it shows a plumose or vermicular habit suggesting its later formation.

Hornblende is occasionally met with as a few green allotriomorphic grains. Fluorite occurs as anhedral grains, sometimes elongated along the marginal planes of other minerals. Sphene, apatite, and zircon occur as small subhedra. Orthite, magnetite, and hematite are rare.

(*b*) *Foliated Granite-gneiss.*—In these rocks biotite occurs in thin wavy and discontinuous streaks, seldom more than 1 inch in length and 0·1 inch in width, and evenly distributed through the rock. Adjoining streaks often enclose more or less lenticular patches of quartz and felspar. In some specimens, coarse-grained pegmatite veins of the same composition as the main rock traverse the gneissic foliation obliquely, thereby showing their slightly later origin. Similar phenomena are shown also by veinlets of slightly coarser quartz and felspar. This suggests that there might have been more than one generation of these minerals. The mineral composition of these foliated granite-gneisses is the same as that of the unfoliated variety described above.

The crystallization of the felspathic constituents in more than one generation is shown in the thin sections. Microcline is usually the last mineral to crystallize, as shown by its relations to oligoclase and quartz, but some sections of oligoclase show inclusions of microcline in optical continuity with adjoining microcline, or have a highly crenulated margin with the latter. It seems in this case that the oligoclase might have crystallized later than the microcline or even have replaced it. True myrmekite has not been observed.

Large quartz grains show undulose extinction but enclose small inclusions of unstrained quartz, and the general relations of the large quartz grains to the normal granitic aggregates of felspars, quartz, and biotite show that the bigger grains have grown at the expense of the original granitic minerals. In some slides, quartz distinctly corrodes plagioclase along the twin-planes of the latter. Biotite usually assumes a reddish brown or darker colour along its margin, a change which seems to penetrate along the cleavage planes of the mineral.

(*c*) *Biotite-rich Granite-gneiss.*—Biotite here occurs in dark bands or patches, thicker and more continuous than the wavy streaks of the rocks just described. These biotitic bands, which are often very regular, alternate with pale felspathic bands, very poor in biotite. Eyes of microcline, 1 in. by 0·5 in., occur in the felspathic bands.

These rocks contain the same minerals as the other two types already described, but in some specimens hornblende forms an important ferromagnesian constituent. Sections of the biotite-hornblende-rich bands show a great variation in the grain-size of all constituents.

The quartz shows strain phenomena. Microcline has perthitic films and stringers ; some of the sections show only incipient twinning, developed especially around quartz inclusions. The plagioclase is an acid oligoclase with less than 17 per cent An. Sometimes it shows a " chessboard-" like structure. Protrusions of oligoclase in microcline often show myrmekitic intergrowths, but the main plate of plagioclase on which the protrusions are based does not always extinguish simultaneously with the plagioclase part of the myrmekite. Thin veinlets of small plagioclase crystals sometimes have peculiar serpentinous courses along the marginal planes between adjoining microcline crystals. These phenomena can be explained by the circulation of soda-bearing solutions towards the end of, or just after, final consolidation.

Biotite is deep reddish brown in basal sections. Marginally the colour may be deeper, and this penetrates inward, taking a suture-like course as it traverses across and along the various cleavage planes. Hornblende occurs in allotriomorphic plates with X = yellowish green and Y = Z = dark bluish green or emerald green. The bigger hornblende plates are sometimes perforated by quartz, sphene, and apatite. Sphene, orthite, zircon, and fluorite are common accessories.

(*d*) *Epidote-bearing Granitic Rocks.*—These rocks are traversed by veinlets of epidote and sometimes show cavities lined with epidote crystals. Some of them are highly kaolinized and very friable. In thin sections, aggregates of epidote intersect quartz grains or ramify through quartz and microcline. Epidote veins enclose numerous angular fragments of these minerals, appearing as a kind of cement. These rocks are characterized by the presence of secondary silica, which in some cases partly fills cavities, in which epidote also occurs. Cryptocrystalline silica largely replaces microcline in some examples, and it seems possible that some of the cavities were created, or at least enlarged, and filled by this replacement process. Magnetite, too, occurs in the cavities and appears to be formed after the crystallization of epidote but before the deposition of the cryptocrystalline silica.

J. A. Dunn (12, p. 121) has observed epidotization in the granitic rocks of North Singhbhum in the neighbourhood of hornblende-schists. He concludes that the epidote has been derived by migration in solution from these schists. Epidotized granites have been recorded by L. A. Iyer (13, p. 499) and M. S. Krishnan (14, p. 114) along crush-zones in the granite-gneisses of Ranchi and Gangpur respectively. In the Kodarma area, some epidote-bearing granitic rocks are from localities where the dome-gneiss contains many inclusions of amphibolite, and has absorbed some of them with the production of hornblende-gneiss. This association, and the brecciated nature of the epidote rocks themselves, suggest that the epidote may have been formed by the alteration of the hornblende of the dome-gneiss along shear-zones at the time of crushing.

(*e*) *Schistose and Aplitic Muscovite-biotite-gneiss.*—These are light coloured and fine grained. Some are finely foliated, the felspathic portion forming minute lenticular patches along the foliation planes. In the unfoliated varieties, large felspathic patches lie in a fine-grained ground-mass containing evenly distributed biotite, muscovite, and sometimes garnet. Lithologically these rocks show more resemblance to the mica-schists and gneisses of the country-rocks than to the dome-gneiss; in thin section, however, their composition is similar to that of the granite-gneiss except that muscovite occurs in appreciable quantity and garnet is an important accessory.

Myrmekitic intergrowths of quartz and plagioclase are often observed. Pseudomyrmekitic drops of quartz occur in plagioclase, or at contacts of plagioclase and microcline ; such drops may be present in one inclusion of plagioclase in microcline and absent from another. It thus seems that these myrmekite-like drops of quartz do not indicate the liberation of silica during the replacement of microcline by oligoclase. The microcline is perthitic. Biotite is strongly pleochroic from yellowish brown to dark brown. Muscovite occurs either in parallel orientation with biotite or its flakes cut across those of biotite. Sometimes muscovite seems to have replaced biotite, and both are being replaced by quartz which has worked its way along their cleavage-planes. Vermicules of quartz in muscovite flakes are regarded as evidence of replacement of muscovite by quartz. Orthite, zircon, apatite, and garnet are the common accessories. Occasionally portions of oligoclase have been replaced by a fibrous zeolite.

These muscovite-biotite-gneisses differ from the country-rocks, mica-schists and gneisses, in having an abundance of felspars, especially microcline. They differ from the granite-gneiss in the presence of abundant muscovite, their fine grain and their occasionally schistose texture. They seem to represent an intermediate type between granite-gneiss and muscovite-biotite-schist, but it cannot be definitely said whether they represent the marginal foliated facies of the granite-gneiss or the highly injected country-rock near its junction.

(*f*) *Granulitic Hornblende- and Biotite-gneisses.*—These are light-coloured fine to medium grained rocks, composed of a granulitic quartz-felspar matrix in which biotite flakes or slightly elongated hornblende prisms are disseminated. Sometimes the ferro-magnesian minerals are arranged in definite linear streaks or bands.

These rocks are composed of quartz and plagioclase almost in equal proportions, and hornblende or biotite or both. Sometimes microcline occurs in appreciable amount. Accessory minerals, sphene, orthite, epidote, zoisite, garnet, magnetite, and ilmenite, are common. The plagioclase, in subhedral plates, is more basic than that of the granite-gneisses, and varies from basic oligoclase to acid labradorite. Quartz and felspar usually show a coarsely granulitic texture, their grains showing interlocking margins. Microcline, if present, occurs as small inclusions in plagioclase or as thin films completely surrounding the inclusions of quartz in plagioclase. Sometimes it runs along the margin of two plagioclase grains, and surrounds the small crystals of quartz occurring along that margin. It thus seems as if microcline crystallized later from potash solutions in these positions. Hornblende, strongly pleochroic with X = yellowish green, Y = dark green, Z = bluish green, forms subhedral or anhedral plates. Biotite is a deep brown variety and occurs either alone, or associated with hornblende along definite linear bands. The margins of both minerals are highly dentated against quartz and felspar. Orthite is a common accessory in rounded grains or anhedral prismatic sections. Brown sphene occurs as strings of rounded grains. Magnetite and ilmenite are often surrounded by hornblende or sphene. Apatite, zoisite, and zircon occur as inclusions in quartz or felspar. In some rocks, especially the banded types, garnet is an important accessory.

The specimens come from the neighbourhood of amphibolite masses, but the area has not been mapped in sufficient detail to bring out their relation to either the granite-gneiss or the amphibolites. The peculiar mode of occurrence of microcline and the variation in amount suggest that the original composition has been affected by the granite magma.

(*g*) *Biotite-hornblende-gneiss.*—These are coarse-grained dark grey rocks, rich in biotite and hornblende, and sometimes having a dioritic appearance. White veinlets of microcline-pegmatite traverse some of the specimens. The gneisses are coarser than the biotite-rich granite-gneiss described above, the ferromagnesian minerals are more evenly distributed, the grain-size is more constant and the plagioclase in them is an acid andesine.

These gneisses are essentially composed of biotite, hornblende, plagioclase, microcline, and quartz in granoblastic association. Biotite, pleochroic from pale yellow to dark yellowish brown, occurs in more or less elongated flakes. Hornblende is greenish blue. The proportions of soda-lime and potash felspars vary in different specimens. In some, microcline is dominant, in others plagioclase. Myrmekite is often seen, indicating that the plagioclase in question crystallized after the microcline; rims of microcline around enclosures of quartz in plagioclase suggest, however, that here the plagioclase is of earlier growth. The accessory minerals are apatite, orthite, zoisite, epidote, zircon, magnetite, and ilmenite.

The specimens described all come from areas where amphibolite inclusions occur inside the dome-gneiss. There are also innumerable pegmatites traversing the rocks of these areas. It seems, therefore, that these gneisses represent, at least partly, mixed rocks. The original amphibolites might have been highly injected by acid magma so that recrystallization has taken place, and most of the hornblende has changed to biotite. Biotite selvages at the contacts of granite-gneiss or pegmatite and amphibolite have been observed at many places.

(ii) *Origin and Correlation of the Dome-Gneiss.*

It is clear that the dome-gneiss is not all of igneous origin and that parts of it must be regarded as migmatitic. The dome-gneiss is essentially a granite-gneiss consisting of microcline, quartz, acid oligoclase, and biotite, with or without hornblende, and with fluorite as a noteworthy accessory.

The relations of quartz and felspars are of interest. In many specimens, the margin of quartz and oligoclase is highly dentated and, in some, quartz has replaced the felspar along the twin-planes. Whilst pseudomyrmekitic drops of quartz in oligoclase are seen in almost all specimens of the granite-gneiss, true myrmekite is seen only in distinctly foliated rocks. Myrmekitic intergrowth of quartz and plagioclase in the granite-gneiss of other areas in Bihar has been differently explained by various authors. J. A. Dunn (12, pp. 104–5) calls it a sort of diablastic structure which is entirely metamorphic in origin, and resulting from the recrystallization of granulated material around the crystals and its reaction with them. L. A. N. Iyer (13, pp. 510–15) thinks that myrmekite is the result of the interaction of the two felspars aided by magmatic juices and that it belongs either to the waning phase of the plutonic activity or to the beginning of the later metamorphic period.

True myrmekite in the dome-gneiss of Kodarma occurs always in foliated varieties and has, therefore, some relation to the process of metamorphism. Certain observations in Kodarma are relevant. All the quartz inclusions often do not have the same optical orientation, whilst the oligoclase protruding into the microcline is often not in optical continuity with the main plate of oligoclase adjacent to it. Further, a big plate of oligoclase surrounded by microcline sections always shows a zoned margin at its contacts with the microcline, but myrmekite-like drops of quartz occur only at one of its corners in contact with a particular crystal of microcline. If replacement of potash-felspar by soda-felspar has occurred, therefore, it seems that the replacement does not always give rise to the simultaneous deposition in plagioclase of the liberated quartz. Some of the quartz drops may be due to the later replacement of oligoclase by quartz, since there is good microscopic evidence that such a replacement is general in these rocks. It must be recalled that myrmekite-like quartz occurs in muscovite in certain varieties of gneiss, suggesting that myrmekitic intergrowth is not confined to interaction of felspars alone.

The banding seen in the biotite-rich varieties of the dome-gneiss has been explained in various ways. Some petrologists regard it as the result of a sort of rhythmical precipitation of mafic and salic constituents of an originally homogeneous magma. Thus Sir Thomas Holland (4) considers the dark bands of the dome-gneiss as " autoliths " formed by local concentration of the mafic constituents. He believes that there is no definite banding of alternating layers so characteristic of the schists, and that the changes observed in the rock " are not profound enough to merit the use of the term metamorphic ". J. A. Dunn (12, pp. 122–3) explains the banded nature of the Chota Nagpur granite-gneiss by the lateral squeezing out of acid magma from the pores of a sponge-like mass of ferromagnesian minerals and felspar. The minerals and " pores " form themselves into alternately linear arrangements and as the pressure continues to be applied the " pores " of still molten acid rock approach one another laterally and ultimately coalesce, forming continuous layers of molten acid rock separating the layers of solidified basic rock.

With regard to the dome-gneiss, the evenly distributed wavy streaks of biotite are probably due to pressure exerted in the granitic magma during its consolidation. In the biotite-rich variety, the texture of the dark bands, composed of coarsely crystallized biotite and hornblende with interstitial quartz and felspar, seems to be more metamorphic than igneous in character. The pink felspathic bands also have certain metamorphic characters, and there is evidence of the operation of soda and silica solutions. If these solutions had originated by squeezing out of the acid molten magma after the consolidation of the mafic constituents and most of the felspars, we should expect them to be mainly potash-bearing. D. R. Derry (15) has suggested, however, that the differentiation of a granite-magma may give rise to a residual liquid rich in soda-felspar. Such solutions may have been responsible for some of the textural features of the dome-gneiss. Though they might have been injected into the rock towards the end of the plutonic activity, they must have promoted the interaction of minerals at least near margins, an interaction of which many examples have been given above.

Some of the specimens of dome-gneiss, especially the biotite-rich foliated type, resemble lithologically the injection granite-gneisses described by H. H. Read (10) from Central Sutherland, Scotland. Read considers these rocks as resulting from the more or less complete mixture of the magma with pelitic or semi-pelitic sediments. A migmatitic origin for the streaky gneisses of Nagpur, Central Provinces, has been advanced by West (16) and recently M. S. Krishnan (14, p. 116) has described migmatization phenomena at the borders of granitic intrusions in Gangpur State. J. A. Dunn (12, pp. 124–6) described hybrids of mica-schist and granite from the Ranchi area in 1929.

Though the dome-gneiss has not yet been mapped in detail, certain characters suggest a migmatitic origin for part of it. Great variation in texture and grain-size, its heterogeneity, the gradation of biotite selvages into biotite-streaks near amphibolite inclusions, and other features suggest that in places the granite magma has been contaminated with country-rock.

The Kodarma dome-gneiss may be correlated with the Chota Nagpur granite-gneiss of the Singhbhum and Ranchi districts and the post-Dharwar granite-gneiss of Gangpur State, described by Dunn, Krishnan, and Iyer. The Chota Nagpur gneiss, according to the views of the officers of the Geological Survey of India, belongs to the late Archaean (Post-Dharwar) period, and the Kodarma dome-gneiss can similarly be regarded as of Archaean age, forming one of the facies of post-Dharwar granite intrusions of India.

IV. THE BASIC IGNEOUS ROCKS OF KODARMA

These rocks can be divided into three groups, representing three distinct phases of basic igneous activity. The first, *epidiorites*, are thoroughly recrystallized, and schistose or granulitic textures have been developed. The second, *metadolerites*, comprise partially metamorphosed rocks in which the original ophitic texture has been preserved, but the pyroxene has been granulated and uralitized. The rocks of the third group, *dolerites*, show no signs of metamorphism ; they are interesting in that similar rocks have not been so far reported from the Dharwar areas of Bihar, though they are common in the coalfields of this province.

(i) *Epidiorites.*

In the present paper, the author follows Wiseman's (17) nomenclature of the metamorphosed basic igneous rocks, and has used epidiorite as a field term and amphibolite as a descriptive term, based on the mineral composition of the rock, for both foliated and unfoliated varieties.

The epidiorites are dark fine to coarse grained rocks, commonly schistose in the fine-grained types. Black hornblende is visible as slender prismatic needles in the fine-grained schistose varieties or as stout prisms in the coarser rocks. Mineralogically, the epidiorites may be subdivided into: (*a*) Plagioclase-amphibolites, (*b*) biotite-amphibolites, (*c*) pyroxene-amphibolites.

(*a*) *Plagioclase-amphibolites.*—These rocks are essentially composed of hornblende and plagioclase with varying amounts of quartz. The plagioclase varies from andesine, approximately $Ab_{60}An_{40}$ to labradorite $Ab_{30}An_{70}$. There seems to be no relation between the amount of quartz and the basicity of the plagioclase. These rocks show porphyroblasts of hornblende of irregular outline embedded in a granoblastic groundmass of felspar, hornblende, and quartz. Linear elongation of these minerals is observed only in the fine-grained variety. The hornblende plates are sieved by quartz and felspar. The mineral s strongly pleochroic with $X =$ yellow or greenish yellow, $Y =$ green or bluish green, $Z =$ greenish blue, the absorption being $X < Y < Z$. In some specimens the hornblende is brownish green, and absorption is $X < Y > Z$. Relics of presumably sahlite structure are sometimes seen.

Magnetite and ilmenite are the most common accessories, usually occurring as irregular inclusions in hornblende. Zoisite in sub-rounded forms occurs in the quartz-felspar groundmass, or as fine needles in quartz. Apatite laths are common. Orthite forms yellowish subhedral prisms in hornblende where it is surrounded by pleochroic haloes. Garnet, brown with a reddish tinge, shows a very irregular outline; it may be sieved by quartz nclusions or may contain highly irregular grains of iron ore or of hornblende.

(*b*) *Biotite-amphibolites.*—These differ from the previous group n the presence of biotite and in the brownish green colour of he hornblende. Biotite is strongly pleochroic from pale yellow o reddish brown and usually has a better outline than hornblende. Though usually biotite does not show any definite vidence of its direct derivation from hornblende, sometimes, owever, it either occurs along the cleavage planes of hornblende r shows no definite boundary against the latter, suggesting that he mica might have been formed from the amphibole.

The main hornblende has $X =$ pale greenish and $Y = Z =$ rownish green. Some of the crystals of this hornblende pass into colourless hornblende with no definite boundary between the two. Other crystals are intersected by, or contain inclusions of, the colourless hornblende with definite boundary. Some crystals are half colourless and half greenish. When the two varieties are in parallel growth, they extinguish at the same time, and both are biaxial negative. It seems that both types belong to the same species with only slight differences in chemical composition. What are presumably relics of pyroxene cleavages are often seen.

The proportion of quartz varies greatly, irrespective of the basicity of the plagioclase. Orthite is a characteristic accessory whilst some of these rocks contain highly irregular grains of garnet.

(*c*) *Pyroxene-amphibolites.*—These are characterized by the presence of pyroxene, in addition to the constituents of the plagioclase-amphibolites. Occasionally they show typical granulitic texture so that they may then be termed pyroxene-granulites.

The proportion of the pyroxene varies, and the mineral is sometimes very unevenly distributed through the slices. It is greenish, non-pleochroic diopside, sometimes with good sahlite structure. In some specimens pyroxene and hornblende seem to have crystallized quite independently, whereas in others the amphibole has in part been derived from the pyroxene. The alteration of the almost colourless pyroxene begins along the various 001 planes of parting ; the hornblende is usually in optical continuity with the host, and even though the whole of the pyroxene may be transformed, the parting-planes may be represented by colourless lines in an otherwise green hornblende. The usual pleochroism of the hornblende of these rocks is X = yellowish, Y = green, Z = greenish blue. A colourless amphibole may be associated with the green variety.

The plagioclase is usually a labradorite, but in the granulitic varieties it is more basic and approaches acid bytownite of composition $Ab_{25}An_{75}$. The granulitic specimens containing garnet and epidote greatly resemble the calc-silicate granulites previously described. Here also the proportion of quartz varies, and is not necessarily related to the nature of the plagioclase. The accessory minerals, sphene, magnetite, ilmenite, zoisite, and apatite occur as in the previous types. Orthite is common in the garnetiferous pyroxene-amphibolites. Garnet sometimes occurs as a few brownish isolated porphyroblasts, but in the granulitic varieties it often surrounds diopside or forms a sort of reaction rim between diopside and plagioclase. In the granulitic types, too, epidote and zoisite are abundant and, in places, seem to replace other minerals.

(*d*) *Origin of the Amphibolites.*—The igneous origin of these rocks is shown by the marked discordance between their strike and that of the mica-schists. The dome-gneiss can be seen to disrupt the amphibolite. Moreover, inclusions of amphibolite occur in the dome-gneiss and have been injected by its pegmatites. It is, therefore, suggested that the dyke-like masses of amphibolite represent discontinuous masses of the original dykes disrupted by the intrusion of the dome-gneiss.

It is concluded that the Kodarma amphibolites represent high-grade metamorphic derivatives of basic igneous rocks. Their high grade is shown by the absence of chlorite, the calcic nature of the plagioclase, and the presence of garnet. From the calcic nature of the plagioclase, and the rarity of quartz and members of the epidote group, it is possible that the grade is still higher up the scale than the garnet zone. Wiseman (17, p. 411) has shown that epidiorites of the kyanite-zone are characterized by the absence of biotite and by the more anorthite-rich felspar. The occurrence of biotite in some of the Kodarma rocks, however, does not mean a retrogressive metamorphism in which hornblende has been changed to biotite. The formation of biotite may be due to the injection of potash solutions from the granite or pegmatite magma. The fact that sillimanite-gneisses are common country-rocks of the Kodarma area suggests that the metamorphic grade of the rocks is of the sillimanite zone. But Wiseman has noted that there is commonly a change in colour of the hornblende from green to brown in such epidiorites occurring near granites. The hornblende in the Kodarma amphibolites is usually greenish blue, and possibly there has been some change in its composition due to the late pegmatitic solutions.

The presence of pyroxene in one of the big amphibolite dykes included in the dome-gneiss may suggest that here the hornblende has partly given place to pyroxene under the highest grade of metamorphism. Other amphibolite inclusions in the dome-gneiss, however, are not pyroxene-bearing, and some specimens show that hornblende is being formed from the pyroxene. The usually bluish tint of the amphibole, the existence of green hornblende and colourless hornblende in the same slide, the sporadic distribution of garnet and quartz, suggest that the composition of the original basic rocks must have been variously affected by material derived from the acid magmas.

(ii) *Metadolerites.*

A few small dykes of metadolerite occur in the Kodarma Forest. They are dark massive rocks of doleritic aspect. Microscopically, the metadolerite is a holocrystalline rock consisting of pyroxene and plagioclase usually in ophitic intergrowth; uralite and biotite occur in varying amounts. Olivine is an essential constituent in one specimen. Magnetite and zoisite are the common accessory minerals.

Plagioclase forms long laths, sometimes zoned or showing undulose extinction. Its composition is that of a labradorite about $Ab_{45}An_{55}$. It is sometimes slightly cloudy, or contains inclusions of granules of zoisite, pyroxene, uralite, biotite, and magnetite. The pyroxene includes both monoclinic and orthorhombic varieties. In some rocks the pyroxene is dominantly enstatite, in others a diallagic type. The orthorhombic variety sometimes has a core of dusty pleochroic material, possibly indicating that partial recrystallization of an original orthopyroxene of hypersthene character has taken place. The presence of hypersthene in some of these cores has been confirmed optically. Both enstatite and diallage are invariably uralitized. Commonly the uralitization process has gone further, and biotite has been found in appreciable amount. The process began with the granulitization of the pyroxene, usually along the margins, and the formation of pale green uralite. The uralite afterwards assumed a yellowish brown colour. The original straight margins of the felspars of ophitic associations are usually made irregular by the granoblastic growth of uralite crystals or the granulation of the pyroxene plates.

Biotite, pleochroic from pale yellow to dark reddish brown, usually occurs in clusters of flakes. Occasionally, however, it surrounds the uralite or is formed along its cleavage planes. Thus it appears that the uralite has been changed into biotite. The degree of biotitization, however, varies very markedly. Olivine is seen in only one slice in which it forms sub-rounded colourless grains, surrounded by a reaction-rim. The inner margin of these rims is probably composed of granular enstatite, the outer of brownish uralite. There is no sharp boundary between the olivine and the rim or between the two parts of the rim. Minute grains of magnetite are sometimes arranged along the cleavage planes of diallage, or thin long laths of magnetite occur amongst the aggregates of granular pyroxene and uralite along twin lamellae of felspar. Bigger irregular grains of magnetite occur as inclusions in uralite aggregates and sometimes form the nucleus round which aggregates of biotite are arranged.

Zoisite occurs in minute forms and grains of varying size: swarms of microscopic granules of zoisite cloud the felspar in many cases.

Origin of the Metadolerites.—The original rocks were clearly of doleritic character, but they have undergone an appreciable degree of metamorphism; as shown, for example, by the granulitization, recrystallization, and uralitization of the pyroxenes. The association of patches of biotite with uralite are incidents of thermal metamorphism. Further, the cloudiness of felspars is supposed to be due to thermal or pneumatolytic metamorphism (18) and, again, corona structures are regarded as of secondary or metamorphic origin (19).

The cloudiness of basic felspars in dolerite dykes has been explained by A. G. MacGregor as due to the original iron and magnesia contents of the felspar appearing as iron oxide and ferromagnesian particles during thermal metamorphism of not very high grade. In the Kodarma metadolerites, fine strings of granules of zoisite, pyroxene, uralite, and magnetite not only occur along felspar twin lamellae, but also irregularly traverse cloudy felspars. Along the channels of such granules, the host felspar usually becomes clear of dust. At places the bigger inclusions of magnetite seem to grade into fine magnetite dust. In some cases, too, strings of granular zoisite, pyroxene, etc., have originated from granular aggregates of ferromagnesian minerals adjacent to laths of felspar, in a manner suggesting injection into the felspar during metamorphism. It is therefore possible that the slight cloudiness of the felspar may be the earliest effect of the injection of solutions liberated locally in the rock during the granulation, recrystallization, and uralitization of the pyroxenes.

Tilley (20) regards the dustiness of the felspar in the South Australian metadolerites as due to inclusions of primary pyroxene granules. Further, Tilley regards his metadolerite as derived from dolerites under the highest grade of metamorphism. In the Kodarma specimens, however, the plagioclase has the habit and composition proper to dolerites, no quartz is present, even in the granules, as would be expected if recrystallization and reaction of the plagioclase had taken place, and the felspars are cloudy. All these evidences seem to indicate that the felspar has not been thoroughly recrystallized and that the temperature was not raised to the highest grade.

The corona structure of the olivine can be regarded as a synantectic structure so long as the rim is confined to the olivine at its contact with minerals containing lime. But the rim also occurs at the contact of two crystals of olivine, and it is clear that solutions must have worked their way along the contact planes of the olivine crystals and taken part in the reaction.

The age relations of the metadolerites are not altogether clear. They are younger than the dome-gneiss and seem to be free from pegmatite injection. The pegmatites, however, are quite unmetamorphosed, whilst the metadolerites are certainly metamorphosed rocks. The dome-gneiss magma is regarded as the parent of the pegmatites, and the metadolerite period cannot be placed between the intrusions of the granitic and pegmatitic portions. The pegmatites must have been intruded at the end of the large-scale tectonic events which accompanied the intrusion of the dome-gneiss, and they marked the end of the thermal activity in the area. It is, therefore, difficult to find in this area the agency after the pegmatite intrusion which might have been responsible for the metamorphism of the original dolerite into metadolerite. It may be suggested that the formation of the metadolerites is an example of plutonic metamorphism such as is provided by the Charnockite Series of South India, but further work is necessary before any conclusion can be reached.

(iii) *Dolerite.*

There is only one big dyke of dolerite in this area. It is a dark rock in which black shining crystals of pyroxene, occasionally in clots, and grey laths of felspars can be distinguished. Altered forms are lighter in colour.

Microscopically, the dolerite is composed of plagioclase and augite in ophitic intergrowth with occasional intersertal glassy patches ; magnetite, pyrite, apatite, and chlorite are accessory or secondary constituents. The plagioclase is a labradorite, in twinned and zoned laths, occasionally partly replaced internally by chlorite. Augite is brownish and its shape is governed by the growth of the felspar laths. Replacement of augite by green chlorite and its alteration to yellowish brown limonite are common. Turbid and cloudy patches of glass occur in some slices and contain microlites of felspar and apatite. Magnetite and pyrite usually occur as irregularly margined rods.

It is evident that the dolerite has undergone no metamorphism. There has, however, been some metasomatic activity leading to the replacement, for example, of felspar by chlorite. The solutions responsible for this cannot be connected with any Archaean igneous activity, as similar changes have been observed in the dolerites in the Jharia coalfield. The dolerites differ from the metadolerites in their non-metamorphic character and absence of orthorhombic pyroxene. They are considered to be the youngest phase of igneous activity in the region.

(iv) *Correlation of the Basic Igneous Rocks.*

It is evident that there are at least three phases of basic intrusion in the Kodarma area, epidiorites, metadolerites, and dolerites.

J. A. Dunn (12, p. 147) has also observed three periods of basic igneous activity in Northern Singhbhum, the oldest being represented by the hornblende-schists of the Oldest Metamorphic Series (Lower Dharwars), the second by the Dalma volcanic flows, usually metamorphosed to epidiorites, of the Iron Ore Series (Upper Dharwars), and the third by the Newer Dolerites (Cuddapahs or earlier). The Iron Ore Series is evidently absent at Kodarma, but the epidiorites of the area are intrusive into mica-schists and gneisses considered to be of Lower Dharwar age. The epidiorites are, therefore, younger than the Lower Dharwars and from the widespread occurrence of similar rocks of Upper Dharwar age in other parts of Bihar, they may be regarded as of the same date.

The metadolerites may be correlated with some of the Newer Dolerites of Singhbhum described by Dunn, who regards them as younger than the Singhbhum granite-gneiss, which the present author has correlated with the dome-gneiss of Kodarma. The metadolerites are also post-Dome gneiss and therefore similar in age to Dunn's Newer Dolerites, i.e. Cuddapah or earlier. The Kodarma metadolerites, however, differ from the Newer Dolerites of Singhbhum in the presence of orthorhombic pyroxenes and in the absence of quartz and chlorite.

Hypersthene-bearing dolerites have recently been observed elsewhere in this province by H. N. Ganguly (21) near Hazaribagh, and S. K. Roy (22) near Deoghar. Ganguly considers these rocks as equivalent to the Dalma Traps and, therefore, older than the granite-gneiss. Roy, on the other hand, is of the opinion that they are quite different from the hypabyssal representatives of the Dalma Traps and also from the Newer Dolerites of Singhbhum and are of late Dharwar age.

Dunn has noted that the dykes of Newer Dolerites in Northern Singhbhum are partly altered to epidiorite, whereas in Southern Singhbhum the dykes in the granite and neighbouring Iron Ore Series have remained quite unaltered. This observation may lead some to believe that the metadolerite and dolerite of Kodarma are similar instances of variation in rocks of the same age, and that the Kodarma dolerite may correspond to the unaltered dykes of the Newer Dolerite in Singhbhum. The Kodarma dolerite, however, is here regarded as of much younger age and is correlated with the dolerite dykes in the Gondwana coalfield. This correlation is based upon the complete similarity with regard to texture and mineral composition of rocks for the two areas. The absence of rhombic pyroxene and the presence of mesostasis in the Kodarma dolerite are points strongly in favour of regarding the rock as younger than the Dharwar or (Cuddapah ?) dolerites. As there has been no period of basic intrusion in India between the Cuddapah and the Rajmahal period, the dolerite of Kodarma must at least be as late as Rajmahal (Jurassic) time. Blandford (23) correlated the similar basic activity in the adjoining Gondwana coalfields with the Rajmahal Traps of Jurassic age. Recently Fox (24) has pointed out that the dolerite of the coalfields may belong to the Deccan Trap period of igneous activity. The Deccan Traps are now regarded as of Tertiary age (25, 26, 27).

V. Summary

The oldest rocks of the Government Reserve Forest, Kodarma, are sillimanite-gneisses, mica-gneisses, mica-schists, and calc-silicate-granulites. They represent the metamorphosed products of the oldest Dharwar sediments which are mostly pelitic and semi-pelitic in nature, and contained occasional calcareous bands. The original composition of the pelitic and semi-pelitic rocks has been greatly modified during the injection of the area by magmatic juices, which followed the intrusion of the granite of the dome-gneiss, so that most of them now contain an appreciable amount of oligoclase felspar. It is suggested that garnet in these rocks is of both igneous and metamorphic origin and that the abnormal richness of the country-rocks in muscovite may be due to pneumatolysis.

The dome-gneiss, as a whole, is not a pure igneous rock. It is essentially a fluorite-bearing granite-gneiss, but at many places it is affected by migmatization. There are many examples of the absorption of basic material by the granite-gneiss ; thus, amphibolite inclusions have given rise to biotite-hornblende-gneiss. Many rocks grouped with the dome-gneiss seem to be either mixtures of partly sedimentary and partly igneous rocks, or are inclusions in it. The dome-gneiss has been correlated with the other post-Dharwar granitic intrusions of Bihar and Orissa.

The basic igneous rocks of the area have been assigned to three phases of igneous activity. The oldest took place before the intrusion of the dome-gneiss. They underwent high-grade metamorphism with the sedimentary rocks of the area prior to and during the intrusion of the granite. These rocks have been described under epidiorites, but classified into plagioclase-, biotite- and pyroxene-amphibolites, according to their mineral composition. The second phase of basic igneous activity occurred after the intrusion of granite and pegmatites, and is represented by metadolerite which retains to some extent its original ophitic texture. It is characterized by the presence of orthorhombic pyroxene, granulitization, and uralitization of the pyroxene and cloudiness in the felspar. The third activity took place at a much later date in the form of an intrusion of a dolerite dyke which, except for the results of metasomatic activity, shows no metamorphic changes. It bears a close resemblance to the dolerites of the Gondwana coalfields. These three basic intrusions have been correlated with the Upper Dharwar, Post-Dharwar (Cuddapah or earlier), and Post-Gondwana (Jurassic or Tertiary) intrusions of other portions of Bihar.

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On Fluoborite from Selibin, Malaya

By R. W. Johnston and C. E. Tilley

(PLATE III)

THE Beatrice Mine at Selibin in the Federated Malay States formed a unique type of tin deposit characterized by its richness in cassiterite and the striking paragenesis of its contained minerals. The mine, now worked out, was developed in a pipe representing a replacement of Permo-Carboniferous dolomite near the margin of the Kledang granite of the Kinta Valley and a systematic account of the geology and petrology of the deposit has been given by Mr. E. S. Willbourn, Director of the Geological Survey (F.M.S.).[1] In this account the principal minerals of the pipe were shown to be tremolite, talc, mica, fluorite, and a " hydrated magnesium borate " with cassiterite and arsenopyrite as the chief ore minerals.

The origin of the pipe was ascribed to the action of hot vapours penetrating the dolomite, bringing in tin, sulphur, boron, and fluorine, with tremolite forming the chief skarn silicate ; while the development of talc, mica, and the borate mineral were considered as derived from tremolite at a later stage in the sequence of metasomatism.

The borate mineral was shown by analysis on a concentrate to contain MgO, B_2O_3, and H_2O as chief constituents and some account was given of its physical and optical characters. These data have been supplemented by an analysis carried out at the Imperial Institute in 1932, but the only published statement is that contained in the Report on " Borates " (1933) [2] giving an estimate of the B_2O_3 content. None of the accounts has been sufficiently detailed to establish a formula for the mineral or to identify it with any described borate.

At the request of one of us Mr. E. S. Willbourn has very kindly placed at our disposal specimens of the pipe rock showing the typical paragenesis of the mineral. These have proved suitable for the isolation of the borate and the following account is based on their study as well as on an examination of specimens presented to the Cambridge Mineralogical Museum by Dr. R. H. Rastall.

Fluorine, unrecorded in the earlier analysis, is now shown to be a major constituent and the properties of the mineral identify it as a member of the fluoborite series ($6MgO. B_2O_3. 3(F_2, H_2O)$).

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[1] *Mining Magazine*, 1926, 329–338 ; 1927, 9–15 ; 1931, 338–341 ; 1932, 20–4.

[2] *Imperial Institute Publ.* " Borates " (2nd edition, 1920–1932), 1933, 18.

The minerals with which the fluoborite is found intimately associated include phlogopite, tremolite, talc, fluorite, and dolomite, with arsenopyrite and cassiterite as the chief ore minerals.

In the specimens richest in fluoborite, the fluoborite areas form white or grey aphanitic or microcrystalline masses interspersed between arsenopyrite and/or cassiterite. Examined in slice the commonest associate of the colourless fluoborite is seen to be phlogopite in small idioblastic plates. The fluoborite commonly appears in a felted mass, the fibres of the felt, usually of length of the order of 0·1 mm., showing negative elongation and moderate birefringence (Plate III, Fig. 2).

When the mineral is enclosed in dolomite or fluorite idioblastic crystals are developed: these then exhibit hexagonal symmetry and elongation in the prism zone (Plate III, Fig. 1). The crystals may reach a length of 1 mm. and breadth 0·1–0·2 mm. Exceptionally, larger crystals may be found forming a fringe of grains surrounding arsenopyrite. Signs of cleavage are very uncommon but some of the larger crystals show traces of a prismatic cleavage which might also be inferred from the examination of crushed fragments of the mineral. The mineral is uniaxial negative, the refractive indices determined by immersion methods being $\omega = 1{\cdot}530$, $\epsilon = 1{\cdot}507$.

The specimen from which the fluoborite analysed has been extracted, contains the following minerals: arsenopyrite in large crystals set in a dense white matrix composed of felted fluoborite in which are scattered small flakes of phlogopite. A little residual tremolite pierced by slender needles of fluoborite, some fine-grained dolomite and a little fluorite are also present.

Other specimens show talc and cassiterite in association with fluoborite. Talc development can usually be traced to alteration of tremolite and it seems clear that the production of fluoborite with its accompanying phlogopite is in some cases partly at the expense of the amphibole. It would appear, however, that fluoborite may be produced by direct action of boron- and fluorine-bearing vapours on the dolomite, exemplified by specimens showing a contact against crystalline dolomite. In these a zone of felted fluoborite with interspersed arsenopyrite in stringers and scattered phlogopite and fluorite passes out into a zone of fine-grained turbid dolomite eventually giving place to the clear dolomite of the country rock. There is no indication in these specimens of any anterior development of tremolitic amphibole.

An almost pure concentrate of the mineral was obtained after treatment on the electro-magnetic separator by dry vanning and final separation in the centrifuge. The resultant powder contained only a very small amount of phlogopite which could not be completely removed in the centrifuge. The analysis was carried out on material dried at 107° C. with a loss of 0·03 per cent H_2O.

Boron was determined by Chapin's method (on 0·6647 gm.), fluorine by precipitation as calcium fluoride (on 0·7662 gm.), while in the determination of the bases the solution from the main fusion was repeatedly evaporated with methyl alcohol to remove all traces of boric acid (on 0·5472 gm.). For water above 107° C., freshly prepared CaO was used as a retainer for fluorine and the water collected in a calcium chloride tube (on 0·5324 gm.).

The figures for the analysis are given in Table I together with two analyses of fluoborite from Tallgruvan, Norberg district, and from Sterling Hill, New Jersey, quoted from Geijer [1] and Bauer and Berman [1] respectively.

TABLE I

	1	1*a*	2	3
MgO	62·02	1550	61·65	60·07
B_2O_3	17·67	253	17·90	17·25
F	20·94	551 } 731	9·30	17·60
H_2O	3·23	180 }	10·78	5·22
SiO_2	0·88	15	0·45	—
Al_2O_3	0·92	9	0·90	—
Fe_2O_3	0·36	2	0·81	—
FeO	1·16	16	—	2·41 (ZnO)
CaO	0·56	10	—	1·19
CO_2	—	—	1·36	1·23
MnO	—	—	0·05	1·93
	107·74		103·20	106·90
$O = F_2$	8·82	F : OH =	3·92	7·41
	98·92	3 : 1	99·28	99·49

1. Fluoborite, Beatrice Mine, Selibin, Federated Malay States. Analyst—R. W. Johnston.
2. Fluoborite, Tallgruvan, Norberg District, Sweden.
3. Fluoborite, Sterling Hill, New Jersey.

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[1] *Sver. Geol. Unders., Årsbok* 20 (1926), No. 4, 1927, 26–9; *Amer. Min.*, 1929, xiv, 169–172.

In this analysis alkalis (K_2O) were not estimated, partly accounting for the low summation, while it is possible that the fluorine determination may be a little low. The analysis leads to the formula $MgO : B_2O_3 : (F_2, H_2O)$ 6·12 : 1 : 2·89 or 6·03 : 1 : 2·81 if SiO_2 and oxides equivalent for phlogopite are removed as such and residual FeO, CaO, and Al_2O_3 added to MgO and B_2O_3 respectively. In the light of the optical data already given the analysis clearly establishes the mineral as a fluor-rich member of the fluoborite series (F : OH = 3 : 1).

The influence of increasing fluorine replacement in raising the specific gravity and lowering the refraction in the isomorphous group is indicated by the following data :—

	F : OH	Sp. Gr.	ω	ε	K
Norberg . . .	5 : 12	2·89	1·566	1·528	0·191
Sterling Hill . .	3 : 2	2·92	1·547	1·522	0·185
Selibin . . .	3 : 1	2·95	1·530	1·507	0·177

The specific refractivities are given under K, the calculated values of K for the hydroxy and fluor end members of the series being 0·224 and 0·156 respectively.

At Tallgruvan, Norberg, fluoborite is recorded with chondrodite and ludwigite, at Sterling Hill in veins with mooreite and pyrochroite. Still more recently Watanabe [1] records the mineral from Korea in association with ludwigite, szaibelyite, and kotoite. In the specimens from Selibin neither ludwigite nor szaibelyite have been observed.

DESCRIPTION OF PLATE III

Fig. 1.—Fluorite-bearing fluoborite-phlogopite rock, Selibin, F.M.S. Idioblastic crystal of fluoborite set in fluorite (left), (right below), felted fluoborite with phlogopite, dark areas arsenopyrite and turbid carbonate. × 32 ordinary light.

Fig. 2.—Phlogopite-fluoborite rock, Selibin, F.M.S. Felted fluoborite enclosing phlogopite and some dolomite ; dark areas (bottom left) dolomite, which encloses sub-idioblastic fluoborite. Some arsenopyrite is also present. × 32 crossed nicols.

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[1] *Min. Petr. Mitt.* 1939, l, 450

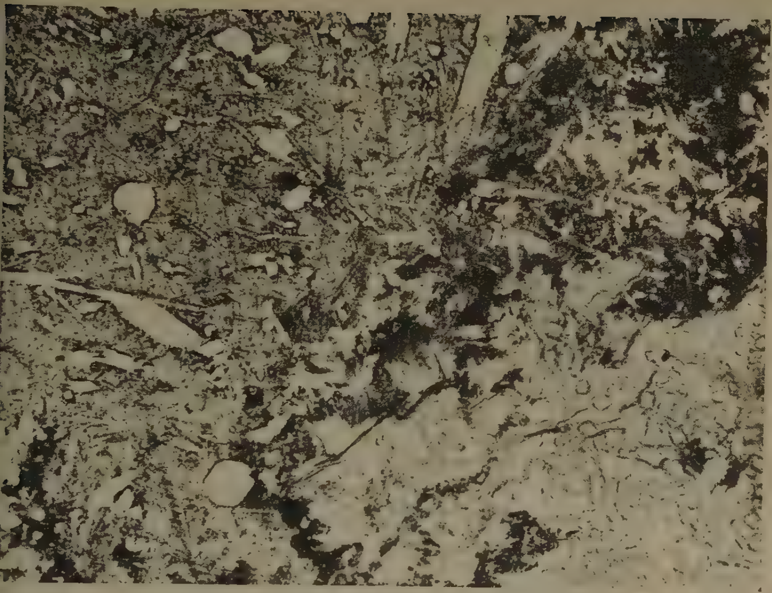


FIG. 1.—FLUORITE-FLUOBORITE ROCK

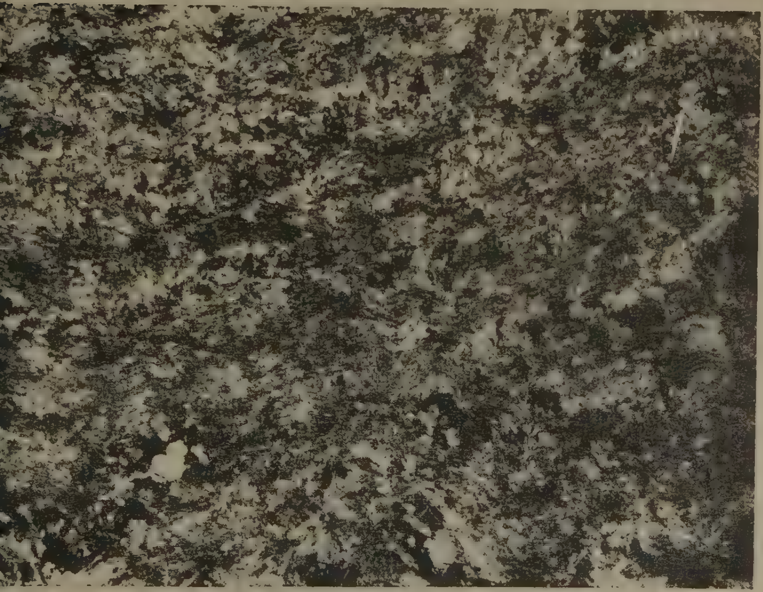


FIG. 2.—PHLOGOPITE-FLUOBORITE ROCK

Mineralogy of Some Permian Sediments from Western Australia

By H. G. Higgins and Dorothy Carroll, University of Western Australia

Introduction

It has been found in many places that the mineralogy of a series of sediments varies according to the time of its deposition ; and basal beds may not contain the same minerals, particularly the heavy minerals, as the upper beds of a series. This investigation was undertaken to see if there was any such variation throughout the vertical thickness of part of the Permian of North-West Australia.

The specimens were collected during the course of detailed geological mapping of part of Wandagee Station (Text-fig. 1), by Mr. E. P. Utting and one of us (H. G. H.), under the direction of Dr. C. Teichert.

Marine Permo-Carboniferous beds outcrop over an area of about 18,000 square miles in the north-west of Western Australia. The maximum thickness is about 8,400 feet and the beds are believed (9, p. 166) to rest on a pre-Cambrian complex of granite, gneisses, and schists.

The greater part of this Permo-Carboniferous area has not been mapped in detail, although the outlines have been given by Raggatt (9) from whom the following brief statement of the stratigraphy is taken :—

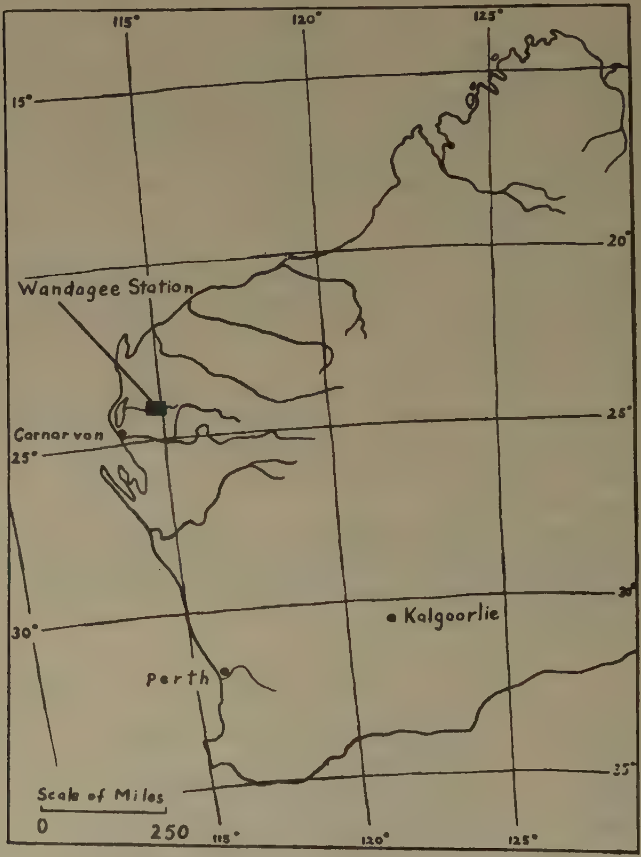
Gascoyne Series

		Max. thickness (feet).
Wandagee Stage .	Marine shales and argillaceous sandstone. Fossiliferous horizons.	2,300
Kennedy Stage .	Massive argillaceous and micaceous sandstone ; marine, few fossils.	700
Byro Stage .	Sandstones and shales, marine. Thin-bedded marine sandstone and sandy to carbonaceous shales. Partly fresh-water ; small erratics.	2,300
Wooramel Stage .	Sandstones with pebble bands, marine	130-280
Callytharra Stage .	Flaggy limestones and calcareous shaly mudstones. Richly fossiliferous, marine.	200–400

Lyons Series

	Shales with sandstones and limestones (300 feet). Fine sandstones with glacial boulder beds and shales ; erratics up to 12 feet.	2,150–2,400

The presence of *Helicoprion* (10, 11) in the Wandagee Stage suggests correlation with the Artinskian. The Lyons Series is possibly Upper Carboniferous, and may be the equivalent of glacial deposits in other parts of the Gondwana continent, such as the Lochinvar tillite of New South Wales (4, p. 511).



TEXT-FIG. 1.—Outline map of Western Australia showing the position of Wandagee Station.

The area shown in the sketch-map is about 300 feet above sea level, and is part of an extensive plain with one prominent hill, Wandagee (583 feet). The plain, of which the area described is only a very small part, is considered by Jutson (5, p. 60) to be a peneplain.

This paper deals mainly with the mineralogy of beds from the type section of the Wandagee Stage (along the Minilya River) and from the vicinity of Carnarvon Road. In addition, some specimens were collected from the beds of Wandagee Hill, and one each from the Kennedy and Byro Stages (see Text-fig. 2). The Wandagee Hill beds are thought by Raggatt (9) to belong to the Kennedy Stage, and therefore to underlie the Wandagee Stage.

In the area mapped the beds have been moderately folded, along generally north-trending axes. The maximum dip, except in the vicinity of major disturbances, is 25°, and the regional dip is to the west, but faults with throws of 1,000 to 2,000 feet occur (Text-fig. 2).

The Wandagee Stage, consisting of over 2,000 feet of marine sediments is divided by the fauna into three main zones, the Lamellibranch, the Calceolispongia, and the Lingula zones. The sediments are all fine-grained, silty, argillaceous sandstones, with or without lime. Many are micaceous; some are platy fine sandstones grading into shales; others are argillaceous limestones.

The rocks from Wandagee Hill (specimens 17 to 21) are generally coarser in grain than the other rocks from the area.

The majority of the specimens were collected from the various zones of the Wandagee Stage in the country north of Wandagee Hill, to ascertain if changes in mineralogy accompanied the palaeontological zones. If the mineralogy of each zone is distinctive, then the stratigraphic position of unfossiliferous beds could be traced from place to place.

The lithology of the Wandagee Stage zones, from above downwards, is as follows:—

Lamellibranch zone.—Ferruginous sandstones grading into calcareous sandstones and passing downwards into sandy shales, fine-grained micaceous sandstones with massive yellow micaceous sandstone at the base. There is a *Fenestella* [1] sub-zone in the upper part, and lamellibranchs are abundant at one horizon. Thickness 500–980 feet.

Calceolispongia zone.—Dark slightly carbonaceous shales passing down into ferruginous and calcareous fine-grained sandstones and micaceous shales. Characteristic fossils are *Strophalosia* in the upper part, *Aulosteges* in the lower, with *Calceolispongia*. Thickness: 400–760 feet.

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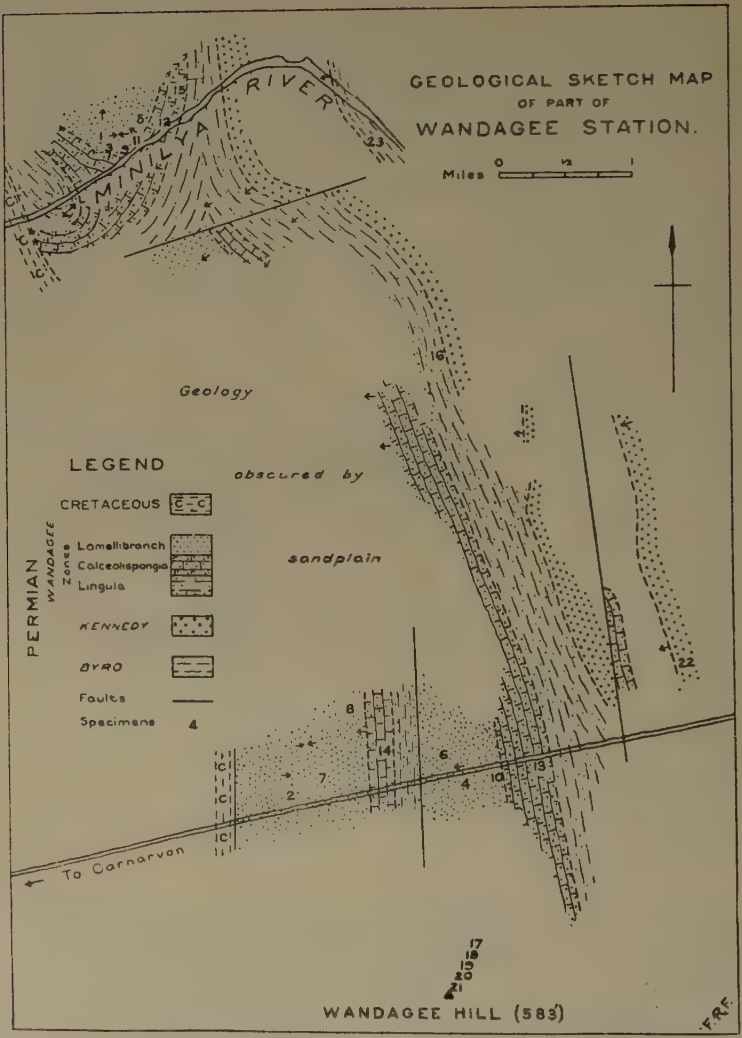
[1] Details of the palaeontology will be published later.



TEXT-FIG. 2.—Geological sketch-map of part of Wandagee Station showing the positions of specimens examined. (Based on fieldwork by C. Teichert, E. P. Utting, and H. G. Higgins, 1939.)

Lingula zone.—Mainly blue gypseous shales with ferruginous partings and a thin-bedded sandstone at the base. Characteristic fossils are *Lingula* and certain foraminifera. Thickness: 470 to 570 feet. Fossils abundant in the Wandagee Stage, but common to all zones include *Chonetes* spp. and *Spirifer* spp.

TABLE I.—HEAVY MINERALS IN THE WANDAGEE BEDS

Sample No.	Index Figure	Magnetite	Ilmenite	Limonite and Leucoxene	Zircon	Tourmaline	Rutile	Anatase	Brookite	Garnet	Titanite	Monazite	Chlorite	Mica	Epidote	Staurolite	Andalusite	Amphibole	Spinel
	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%	%
1	0·71	+	5	24	39	2	4			20	1	1			+				+
2	Tr.	+	3	19	56	4	4	+		5	5	2			+				
3	0·55	+	3	22	50	6	9	1	+	5	5	+	+						
4	0·45	+	1	34	32	5	9	+		14	2	+	+			+			
5	0·30	+	1	28	44	7	6	+	+	10	1	1			+				
6	1·00	+	1	46	26	2	3	+		14	3	1							
7	0·80	+	4	40	22	5	3	+		21	3	+							
8	0·57	+	11	28	27	3	3			25	+	+		1		+			
9	Tr.	+	1	37	36	2	6	2		12	3								
10	1·00	+	9	23	26	5	4			31	1								
11	Tr.	+	8	34	29	2	3	1		20	1			+	+				
12	Tr.	+	7	33	34	5	2	2		13	1	+	+						
13	Tr.	+	4	40	16	6	4	1		23	1			3	1	+		+	
14[1]	Tr.	+	16	77	5					+	+				+	+			
15	Tr.	+	5	54	27	4	2	1		8	1			+	+		+		
16	Tr.	+	6	26	19	6	4	1	+	35	+	+		1	+	+			
22	Tr.	+	1	15	40	3	5			34	+	+	+	+					
23	Tr.	+	1	17	46	1	7	+		26	+	+			+				
17	Tr.	+	13	53	20	7	5			+	+			+	+				
18	1·31	+	2	55	10	2	2		23	1	1	2			+				+
19	1·20	+	23	36	25	4	1	1		+	4	3							
20	2·00	+	24	36	28	1	3	+		2	2	2			+				+
21	0·13	+	22	30	31	4	4	+		6	1	+		+	+				

+ = less than 1 per cent. Index Figure = % by weight heavy residue; Tr. = Trace.

Samples 1–10 incl. are from the Lamellibranch zone; Nos. 11–15 incl. from the Calceolispongia zone; No. 16 from the Lingula zone; of the Wandagee Stage. Nos. 22, 23 from the top of the Kennedy Stage or base of the Wandagee; Nos. 17–21 incl. from the Kennedy Stage at Wandagee Hill.

[1] Only a very small amount of material was examined.

MINERALOGY

Heavy Mineral Residues and their Varietal Features

Practically every rock examined was fine-grained. Each specimen was crushed and the material passing an 85 B.S. sieve (approx. 70 I.M.M.) was washed to remove the very finest, clay-grade grains, and treated with acid to remove the carbonates and limonite. About 20 grams of each cleaned sample was separated in bromoform to obtain the heavy residue, which was also weighed to obtain the Index Figure (Table 1). Magnetite was removed by a small electro-magnet before the residues were mounted in balsam. The percentage mineral composition (Table 1) of each residue was obtained by counts involving about 500 grains. It will be seen that the outstanding features of these residues are the abundance of zircon and garnet, the constant presence of ilmenite, limonite, leucoxene, tourmaline, rutile, titanite, and to a lesser extent of monazite and anatase. The other minerals, with the exception of brookite in one sample, occur only as odd grains.

The histograms (Text-fig. 3) give a clear picture of these results. There is seen to be very little change in the mineralogical composition throughout the beds, hence the area was one of even and continued sedimentation during this time, although, as indicated above, there are three definite fossil zones.

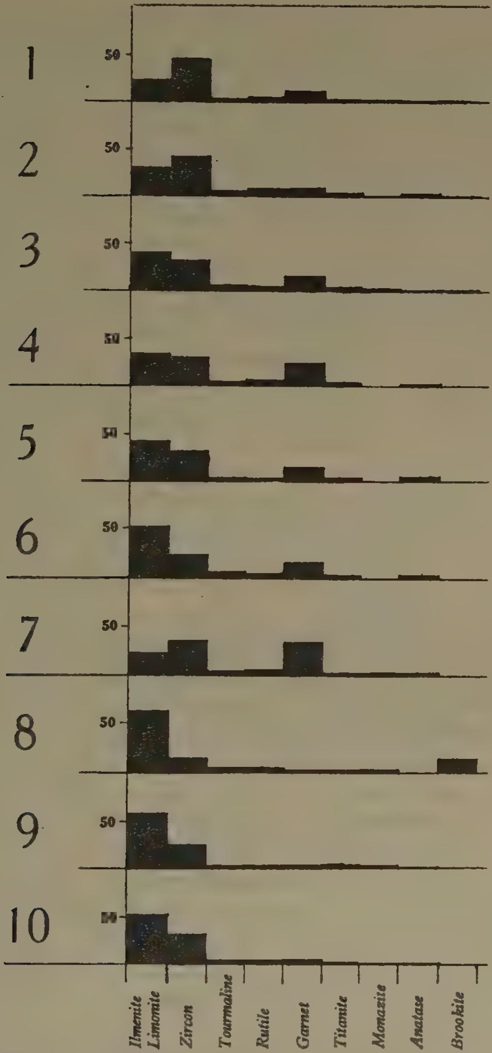
On looking more closely at the percentage compositions of the residues, however, it will be seen that there are differences in mineralogy between the Wandagee Hill sediments, and the beds of the Wandagee Stage itself.

In Text-fig. 3 the specimens from the bottom of the Wandagee Hill beds to the top of the Wandagee Stage are placed as far as possible in their correct stratigraphic sequence. The main difference is in the garnet content ; there are also distinct varieties of zircon and garnet in the Wandagee Hill beds. The validity of this distinction will have to be tested with a greater number of specimens, before being finally accepted. Many of the minerals show marked varietalism which may be distinctive for these sediments, when more material from below the Wandagee Stage has been investigated.

Details of the Minerals

Magnetite, *ilmenite*, *limonite*, and *leucoxene* show no features of varietal interest.

Zircon : Small, well-rounded grains are found in every residue ; some of the grains are almost spherical, whereas



TEXT-FIG. 3.—The histograms represent average heavy mineral assemblages of the specimens arranged stratigraphically from the base of the Wandagee Hill beds to the top of the Wandagee Stage.

Lamellibranch Zone.—(1) (Specimens 1 and 2); (2) (Specimens 3 and 4); (3) (Specimens 5, 6, 7); (4) (Specimens 8, 9, 10).

Calceolispongia Zone.—(5) (Specimens 11, 12); (6) (Specimens 13, 15).

Lingula, Kennedy, Byro.—(7) (Specimens 16, 22, 23).

Wandagee Hill Beds.—(8) (Specimens 17, 18); (9) (Specimens 19, 20); (10) (Specimen 21).

others have only had the sharp crystal outlines smoothed off. The zircons in the Wandagee sediments are generally very small in size, some are zoned, but the majority are clear and colourless with few inclusions, which if present, are in the form of rounded bubbles and rod-like colourless inclusions. Occasionally tawny grains are prominent as in *specimen 10* from near the base of the Lamellibranch zone, and in the *Calceolispongia* zone. Sometimes " double grains " occur, i.e. individuals joined parallel to the *c* axis ; and sporadically there are squarish, fresh to well-worn prismatic grains. The colour in some grains is strong enough to suggest xenotime, but there is insufficient material for a chemical test. The zircons in the Wandagee Hill sediments are generally larger in size, robust in habit, and many are purple. Generally these purple grains are well-worn ; some are zoned, others are clear with a few inclusions. Purple zircon is not uncommon in some Western Australian sediments ; it occurs in the Cretaceous Gingin Chalk and Greensand, the Irwin River Coal Measure sediments, and in the lower Tertiaries of the Swan Coastal Plain at Perth. In the Wandagee Hill sediments small colourless zircons are also present.

Tourmaline : Makes up from 1 to 7 per cent of the heavy residues and occurs in brown, grey, and blue broken fragments, rounded grains, and prismatic fresh and worn grains. Generally the brown and grey strongly pleochroic grains are more abundant than the blue. The distribution of the varieties of tourmaline was tabulated, but it was found that there is rather a uniformity throughout these residues, from the top to the bottom of the series. Nevertheless the *Calceolispongia* zone contains only brown and grey tourmaline. Parti-coloured blue and brown grains, generally in broken fragments, occur mostly in the Lingula and Kennedy beds. Blue tourmaline, including a very pale blue strongly-pleochroic variety occurs principally in the Lamellibranch zone and in the Wandagee Hill beds. Little significance can be attached to varietalism in tourmaline as it is a mineral which varies readily according to the environment of its formation. As it is resistant to wear and chemical decomposition it is often present in large quantities in residues. The small percentage in these residues shows that much of the material was " second-hand ".

Rutile, *anatase*, and *brookite* : These related titanium minerals can be discussed together. The rutile in the residues is both authigenic and derived ; anatase and brookite are authigenic only.

Detrital rutile occurs throughout the beds as deep reddish brown, well-rounded grains, often nearly spherical; yellowish brown, rounded prismatic grains; and as occasional broken worn twinned grains. In one residue small rutile rods embedded in chlorite were observed. There appears to be no significance in the distribution of these varieties of rutile throughout the beds, most of which contain both derived and authigenic grains.

Anatase is present in amounts varying from a few grains to 2 per cent. Its presence appears to be sporadic, except that the greatest amount is in the Calceolispongia zone, and least in the Wandagee Hill beds. The grains are generally nearly perfect euhedra of tabular habit, ranging from almost colourless steely grey to bright yellow. The pyramidal habit was not seen. Sharp outlines and euhedral crystals indicate authigenic origin; the grains are usually small, but there are occasional larger grains.

Brookite in beautifully formed prismatic euhedra is a characteristic mineral of *Specimen 18*, a rather coarse sandstone from Wandagee Hill, where it makes up about one-quarter of the residue. The prismatic habit predominates, the crystals being terminated with pyramids and brachydomes which are similar to those in Brammall's illustration No. 3 (1). The two ends are seldom found. The centres of the grains are dense and almost opaque, but with a higher magnification it is seen that this density is produced by parallel and overlapping crystal growth in some instances, and by marked striations in others. Some crystals are attached to masses of opaque material, probably ilmenite, or a mixture of ilmenite and limonite from which they project. There is no sign of wear or abrasion. This brookite is undoubtedly authigenic. In three other beds only a few grains of yellow striated brookite was seen. There is no anatase in the residue with the abundant brookite. Much of the opaque material in these slides may consist of ill-defined authigenic titanium mineral.

Little new work has been done on the genesis of the titanium minerals since that of Brammall and Harwood (2), but leucoxene has recently been examined by X-ray methods (12) and found to be identical with either anatase or rutile. Leucoxene therefore appears to be one of the first steps in the production of anatase, rutile, and brookite. The similarity in behaviour between solutions of silica and titania has been noted by Polynov (8, p. 115) but was first suggested to one of us (D. C.) when examining soil residues some years ago (3, p. 75), but at that time leucoxene was considered to be a form of sphene so that the full significance of the association of the titanium minerals and the conditions of their environment was not realized. As with pyrite, the formation of the titanium minerals in sediments probably requires an acid or reducing environment. The fineness of grain size indicates that these sediments were formed some distance from land in fairly still water, and in the open ocean rather than in closed bays, for the acid reaction necessary for the formation of the titanium minerals was not sufficient to convert the iron ores to pyrite.

Garnet : Next to the opaque grains and zircon, garnet is the most conspicuous mineral in these residues. In the upper part of the Wandagee Stage, and throughout these beds it is present in amounts up to 35 per cent (of the residue), whereas in the Wandagee Hill sediments, there is very little. In the Wandagee Stage garnet occurs in small, colourless, angular fracture chips, which are generally etched. No rounded grains are seen. In the Wandagee Hill residues, the garnet is in larger pinkish-brown grains with smooth outlines and is not etched. The angularity and freshness of all the garnet from the Wandagee Stage is in marked contrast with the roundness of all the other minerals. There are two possible explanations : (1) That the garnet represents new material which was brought in as erosion of the land surface proceeded, the bulk of the heavy residue having come from some sedimentary series which was eroded first. (2) Garnet is a brittle mineral which fractures easily and does not become rounded readily. Although considered to be particularly stable and long lasting in sediments (7, p. 181) the experience of one of the authors (D. C.) with many types of sediments and soils has shown that large quantities of garnet usually occur rather near the source of origin, and that in old reworked sediments, garnet is not nearly as persistent as zircon and tourmaline. Like epidote, larger quantities do not seem to be able to survive more than one cycle of sedimentation.

Titanite occurs throughout these residues in small quantities, the greatest being 5 per cent in the upper parts of the Lamellibranch zone. The grains are chunky and colourless to very pale brown. There does not seem to be much significance in its presence except as an indicator of granitic rocks in the distributive province.

Monazite in typical rounded yellowish green grains is of sporadic occurrence throughout the series, and is most abundant in the Wandagee Hill beds. Like titanite it points to granitic and gneissic parentage.

The remaining heavy minerals, *chlorite*, *mica*, *epidote*, *staurolite*, *andalusite*, *amphibole*, and *spinel* are the minor constituents of the residues. Mica is the most plentiful of these, but will be discussed with the " light " minerals. Spinel is the dark green variety similar to that often found in sediments derived from Precambrian meta-sediments of Yilgarn age. These minerals with the exception of mica represent the " dregs " of some previous sedimentary series which was originally derived from Precambrian schists and gneisses. The scarcity of amphibole and epidote indicates also a second cycle of sedimentation for most of the residual minerals. These points will be discussed more fully when considering the source and origin of the heavy minerals.

The " Light " Fractions

The minerals making up this fraction (and the bulk of the sediments) are quartz, felspar, mica, and clay material. No estimates of the amount of carbonates in the various beds were made, and the clay material was washed out during preparation.

Quartz grains, generally sub-angular, are very abundant, and usually there are a few rounded grains. The grains are clear, but often coated with a thin film of aluminous material which is difficult to remove. Inclusions noted were minute pepper-dust ores, or minute lines of bubbles crossing the grains, but many grains were entirely free from inclusions.

Felspar is present in all material and orthoclase, albite or oligoclase, and microcline were identified. The grains generally are fresh with sharp unworn cleavage edges, although occasional alteration products occur in the centres of some grains.

Mica is abundant as small colourless flakes in nearly all the sediments.

Origin and Source of the Detrital Minerals

The residual minerals of these sediments show that granitic, gneissic, and basic rocks, and possibly an older sedimentary series contributed to the formation of the beds. The fineness of the grain size and the uniformity throughout the mineralogy of the beds indicates slow conformable sedimentation in a quiet sea some distance from the land. The land area eroded to form these sediments was probably to the east of the site of sedimentation, where rocks of the Precambrian shield outcrop at the present time. The rounding of some minerals suggests the erosion of an earlier series of sediments, but there is, up to the present, no geological evidence of older Palaeozoic rocks in this part of Western Australia. The Precambrian rocks, however, contain an ancient sedimentary series of conglomerates, sandstones, and shales with interbedded volcanic lavas and ashes, which is known as the Nullagine series ; and it is probable that the wearing down of these beds supplied a great deal of material for the Permian. Below the Nullagine, and adjacent to the area of sedimentation, is another series of Precambrian sediments, the Mosquito Creek series, which must also have contributed.

" In post-Nullagine times erosion of the series was excessive, and possibly long continued. The strata were cut down until in some cases they were represented by mere isolated outliers ; the horizontal or gently inclined beds have in other places been deeply incised and narrow trenches cut in them . . . often some miles in length . . ." (6, p. 23). The absence of coarse material in the Wandagee sediments shows that they were derived from a terrain of low relief.

In marked contrast to the majority of minerals in the residues, the fresh, unworn garnet grains indicate that garnetiferous rocks, presumably gneisses, were newly exposed to erosion at some time during sedimentation. An investigation of the mineralogy of other members of the Permo-Carboniferous sequence, such as the Kennedy, Byro, and Wooramel Stages will probably throw much light on the present findings and their use as indicators of the Wandagee Stage.

The field-work carried out early this year showed that the stratigraphic position of the Wandagee Hill beds is doubtful. The mineralogy of these beds clearly shows (Text-fig. 3) that they are dissimilar from the Wandagee Stage beds in the amount and type of garnet, and in the type of zircon present. Until further field-work, which will, it is hoped, be undertaken shortly, has clarified the position, the heavy minerals suggest that the Wandagee Hill beds were deposited at the end of a minor sedimentation cycle, and that the new material was available for the Wandagee Stage beds. Raggatt (9, p. 164) is of this opinion from field evidence and states : " After the deposition of the Kennedy sandstones the sea advanced upon the land again, marine life flourished, and a considerable thickness of shales, and calcareous beds was built up."

The presence of felspar of various kinds might be thought to suggest that some of the ideas in connection with the origin of the residual materials were invalid. The bulk of these sediments consists of very finely divided quartz, clay, mica, and felspar. Much of the clay has undoubtedly been transported as clay, and there is some reason to suppose that small felspar grains are rather resistant to alteration after inclusion in a sediment. The felspar was probably contributed by the last eroded gneisses and granites.

The lack of ferromagnesian minerals, such as amphibole, is interesting, for the distributive province contains lavas in the Nullagine Series, and basic dykes in the underlying Mosquito Creek Series. It seems probable that much of the clay material may represent original amphiboles and chlorites in the lavas and associated volcanic ashes. The fineness of grain size may be the result of sorting, whereby the amphiboles remained in the near-shore sediments. Greenstones of the Yilgarn type with abundant bladed, strongly blue-green amphibole, which is resistant to weathering, probably were not present in the eroded terrain, as there is no evidence of them in the Wandagee sediments. The large quantities of opaque grains may represent the basic material, or may have been derived from gneiss along with garnet. Ilmenite, leucoxene, and limonite are minerals common to all types of sediments and have therefore very little significance.

CONCLUSIONS

The main object of this investigation was to ascertain if mineralogical changes accompanied the faunal changes in the beds of the Wandagee Stage. From Text-fig. 3 it is seen that the three zones are not characterized by any striking variation in amount of the heavy minerals present, nor are there any marked changes in habit of such minerals as zircon, rutile, garnet or tourmaline. Text-fig. 3 also shows that there is a distinct mineralogical difference between the Wandagee Hill beds (possibly Kennedy Stage) and those of the Wandagee Stage. Detailed mineralogical correlation of fossil zones does not at present seem possible, but this work has established a type heavy mineral assemblage for the Wandagee Stage, the full value of which will be shown when the type assemblages of the lower stages of the Permian in this area have been examined. By " type-assemblage " is meant the average percentage mineral composition of the heavy residues in the beds described. Such a type assemblage is used as a standard for the mineralogical comparison of one sediment with another.

From Table 1, by averaging the percentage of each mineral in the sediments examined we get the type assemblage for the Wandagee Stage beds. But in mineralogy, as elsewhere, the figure given by the average may conceal large differences ;

for instance, if most of the percentage figures are fairly low, say about four or five, and one or two are very much larger, say thirty, then the average for this particular mineral will be too high for a large number of the specimens examined. In order to give some idea of this variation, the range in percentage has been given in the tabulation below. But even this is not entirely satisfactory, for there may be many specimens in which the figure for any particular mineral is the same or nearly the same.

Statistical methods, as applied to the interpretation of the grading of sediments, provide a means whereby we can show the " spread " or distribution of the percentage figures. If the percentages are arranged in order from the smallest to the largest, then the one in the centre is known as the *median*. As an example, take the percentages for ilmenite from Table 1 :—

$$1,\ 1,\ 1,\ 1\ \underset{Q_1}{(1)},\ 1,\ 1,\ 3,\ 3\ \underset{M}{(4)},\ 4,\ 5,\ 5,\ 6\ \underset{Q_3}{(6\tfrac{1}{2})},\ 7,\ 8,\ 9,\ 11.$$

The range or spread of the distribution of these percentages in the specimens is from 1 at the First Quartile (Q_1), which is one-quarter of the specimens of the total, to 6½ at the Third Quartile (Q_3). That is, in three-quarters of the specimens examined the percentage of ilmenite is between 1 and 6½. It is thought that such a range of percentage for each heavy mineral will be useful for comparison of other material with the object of seeing whether it belongs to the series being examined or to some other assemblage, with a different mineral composition.

The type assemblage of heavy minerals in the Wandagee Stage sediments in percentages is :—

	(Aver.)	*Range.*	*Median.*	*1st Quartile.*	*3rd Quartile.*
Ilmenite	4½	1–11	4	1	6½
Limonite, Leucoxene and Magnetite . .	33	19–54	33	24	40
Zircon	32	16–56	29	26	39
Garnet	16½	5–31	14	10	23
Tourmaline . . .	4	2–7	5	2	6
Rutile	4	2–9	4	3	6
Titanite	2	½–5	—	—	—
Monazite . . .	½	½–2	—	—	—
Anatase	½	½–2	—	—	—
Brookite	—	—	—	—	—
Chlorite, Mica, Epidote, Staurolite, Andalusite, Amphibole, Spinel .	1	0–1	—	—	—

Certain varietal features which distinguish the minerals of this assemblage have been described for the individual minerals.

The uniformity and simplicity of these assemblages are due to conditions of continuous sedimentation in a geosynclinal basin and also to the rocks of the distributive province. The conditions for simplicity of heavy mineral assemblages are admirably fulfilled in the Wandagee beds; the thickness and character of the Permian sediments indicate their geosynclinal origin (11) and the stratigraphic position of the Wandagee Stage shows that it was laid down towards the close of a period of continuous sedimentation, some distance from a shore-line. The distributive province for these sediments included the Nullagine and Mosquito Creek Series (Precambrian). The Nullagine Series consists of sediments such as sandstones and shales with interbedded lavas and ashes, and probably provided the fundamental suite of all rocks described. The origin of the garnet is less certain, though its source may be in the Mosquito Creek gneisses.

ACKNOWLEDGMENTS

This investigation was carried out as part of the research programme initiated by the Commonwealth Research Grant to the University of Western Australia (D. C.), and also as part of a project of the Hackett Research Studentships in this University (H. G. H.), to both of which authorities grateful acknowledgment is made.

We should like to express our very great thanks to Professor E. de C. Clarke for the interest he has shown in this investigation at every stage, and to Dr. C. Teichert for his ready discussion of many difficult points. We are indebted to Mr. F. R. Feldtmann for the preparation of Text-fig. 2.

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The Relation of the Valves to the Pedicle in the Strophomenid Brachiopods

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I. Introduction

THE relation of the valves to the pedicle is among the fundamental characters on the basis of which the phylum Brachiopoda has been divided into five orders (see Thomson, 1927). In a previous paper (Arber, 1939), I pointed out that, on this classification, the order Protremata cannot be regarded as a homogeneous group, since in the orthids the pedicle apparently emerged through an open delthyrium, while in the strophomenid *Leptaena* it emerged through an entirely separate foramen situated in the ventral valve. Schuchert in 1913 (p. 383) defined the whole superfamily Strophomenacea as being characterized by a pedicle which, when present, was small, and emerged at the apex of the valve. A pedicle-foramen is, however, by no means of universal occurrence, and its existence has also been often overlooked in systematic descriptions, so that, in spite of Schuchert's definition, some doubt has nevertheless remained as to whether the form of pedicle-opening found in *Leptaena* and a few closely allied genera is genuinely typical of the whole of the strophomenids, thus creating a developmental distinction between that group and the orthids. I have therefore examined as many as possible of the available specimens and descriptions of the strophomenids, with the results here recorded.

For access to material, I am indebted to the Keeper of Geology, and Dr. Muir-Wood, the British Museum (Natural History), and to Mr. Brighton, the Sedgwick Museum, Cambridge. I am grateful for critical discussions on some of the problems with Dr. O. M. B. Bulman, and with Professor O. T. Jones, F.R.S., who has also kindly given me facilities for work in the Sedgwick Museum.

II. The Occurrence of the Pedicle-Foramen

The classification of the strophomenid brachiopods is at present in an unsatisfactory condition. In the *Fossilium Catalogus* (1929), Schuchert and LeVene gave a temporary arrangement of six subfamilies (Rafinesquininae, Plectambonitinae, Orthotetinae, Triplesiinae, Davidsoniinae, and Tropidoleptinae), grouped under the general heading of King's family Strophomenidae. The Tropidoleptinae have since been assigned to the order Orthoidea (Schuchert and Cooper, 1932), and various authors have proposed other readjustments in the classification, including the elevation of certain of the subfamilies to the rank of families. Nevertheless it seems that some of the " subfamilies " in Schuchert and LeVene's list may have more in common with one another than with the other branches of the superfamily Strophomenacea ; and on this account the list of genera included in the " family Strophomenidae ", as understood by Schuchert and LeVene, with the exception of the Tropidoleptinae, and augmented by more recent discoveries, has been used as a working basis for the present investigation. With certain modifications, the " subfamilies " have been used as convenient units for the grouping of genera, but no precise significance can be assigned to them.

It was not possible to examine specimens of all known species, or even of all genera, and the details of the umbonal structure can only be seen in particularly well-preserved material, and have frequently not been recorded in published descriptions. The following examples are therefore a representative, but far from comprehensive, list of the species in which the pedicle-opening can be shown to belong to the same type as that of *Leptaena*.

In previous literature, precise significance has not always been attached to the terms *supra-apical* and *apical*. In this paper the foramen is described as *supra-apical* when it is separated from the pseudodeltidium by a rim of the brephic [1] ventral valve (see Text-fig. 1 C), and as *apical* when this margin has been resorbed so that the foramen is bounded by the pseudodeltidium (see Text-fig. 1 A).

RAFINESQUININAE Schuchert

In this group a supra-apical or apical pedicle-foramen is commonly found.

Leptaena Dalman

A full account has already been given (Arber, 1939) of the pedicle-aperture in *Leptaena*. It was shown that, in the youngest stages, the pedicle emerged through a foramen which was

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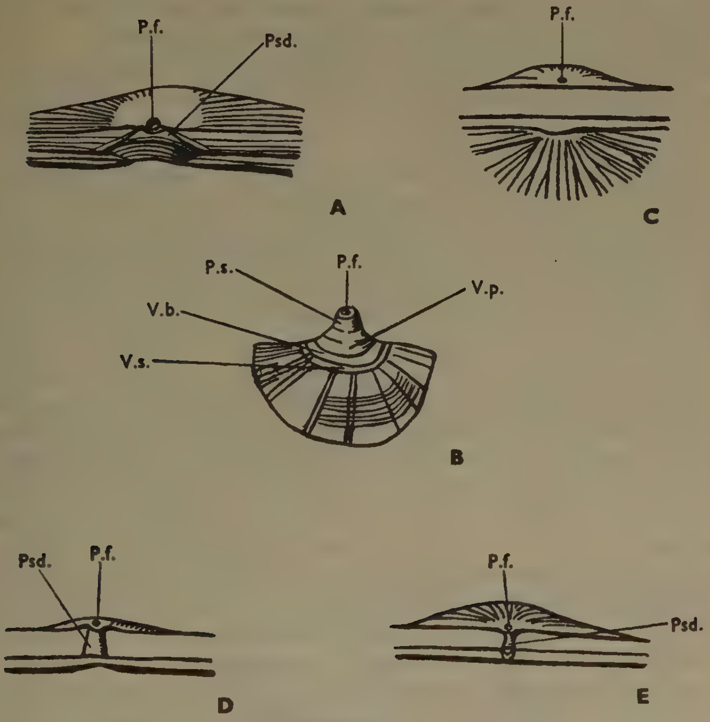
[1] I am indebted to Dr. W. D. Lang, F.R.S., for pointing out to me the greater linguistic correctness of the term *brephic*, proposed by Buckman and Bather (*Zool. Anz. Leipzig*, xv, 1892, pp. 420, 429), for the infantine or larval stage, rather than Hyatt's term *nepionic* which was used in my previous paper.



TEXT-FIG. 1

A. *Rafinesquina alternata* (Conrad); Blue Limestone (Upper Ordovician); Cincinnati, Ohio, U.S.A.; cardinal view of umbonal region (ventral valve uppermost) showing plugged foramen enlarged and now bordered dorsally by pseudodeltidium; × 2. [Brit. Mus. (Nat. Hist.), B. 56158.]

B. *Rafinesquina* (?) sp.; Black *Trinucleus* Shales (Upper Ordovician); Svälasgård, Skattungbyn, Dalecarlia [Dalarne], Sweden; ventral valve of neanic specimen showing pedicle-sheath with scar of foramen; × 8. [Brit. Mus. (Nat. Hist.), B. 46471.]

C–E. Cardinal views of umbonal region; showing scar of supra-apical foramen entirely enclosed within brephic ventral valve; × 4.

C. *Stropheodonta demissa* (Conrad); Hamilton (Middle Devonian); Arkona, Ontario, Canada. [Brit. Mus. (Nat. Hist.), B. 75079.]

D. *Leptostrophia canace* (Hall and Whitfield); Hackberry stage (Upper Devonian), Cerro Gordo substage, *Spirifer* zone; Rockford, Iowa, U.S.A. [Brit. Mus. (Nat. Hist.), B. 41564.]

E. *Douvillina dutertrii* (Murchison); Devonian; Ferrones, Spain. [Brit. Mus. (Nat. Hist.), B. 6369.]

P.f. pedicle-foramen; P.s. pedicle-sheath; Psd. pseudodeltidium; V.b. ventral brephic shell; V.p. ventral protegulum; V.s. ventral neanic shell.

enclosed within the protegulum and brephic ventral valve. The pedicle then either atrophied immediately, or it survived to the neanic or even adult stage, resorbing the margins of its foramen as the animal grew. When it had atrophied, the aperture became plugged by later shell-deposits.

Rafinesquina Hall and Clarke

The presence of a foramen in the apical position has been observed in a number of species, and the earliest description of the strophomenid pedicle-foramen ever given was that of de Verneuil (1845, p. 225), in his account of *Leptaena* [*Rafinesquina*] *alternata* Conrad. Although this species was adopted by Hall and Clarke (1892) as the genotype, the foramen was not mentioned in their diagnosis of the genus. It is, however, commonly present in *R. alternata*, but in the adult it is usually plugged by shell-substance, its margin having been resorbed both dorsally and ventrally (see Text-fig. 1 A). This suggests that the pedicle here survived throughout the young stages, but emerged more or less horizontally, so that the shell rested on its ventral valve. By the time that the adult condition was reached, the pedicle appears almost always to have atrophied.

In the infantine or brephic stage of *Rafinesquina*, the pedicle was presumably enclosed within the protegulum and surmounted by a sheath as it was in *Leptaena*. Such a condition, surviving into the adult (cf. *L. emarginata* Barrande), is found in *R. ulrichi* (James) (see Hall and Clarke, 1892, pl. xv A, figs. 37–8), from the Upper Ordovician of North America. A pedicle-sheath, with the scar of a foramen at its extremity, is also seen in neanic specimens of an unidentified species, probably of *Rafinesquina*, from the Black *Trinucleus* Shales (Upper Ordovician) of Svälasgard, Skattungbyn, Dalecarlia [Dalarne], Sweden (see Text-fig. 1 B).

Sub-genus *Playfairia* Reed.

An apical foramen occurs in *P. semiglobosina* (Davidson) (see Davidson, 1871, p. 287, pl. xli, figs. 5–5*a*), from the Ordovician of Girvan, Ayrshire, Scotland.

Stropheodonta Hall

In *Stropheodonta* and the other crenulate-hinged genera with normal concavo-convexity, there is evidence of the presence of a pedicle in the early stages of growth, but in the adult the foramen is only seen as a small scar. These genera are on the whole later in date than *Rafinesquina*, and it appears that the pedicle did not usually survive so long in the life of the individual.

Beecher (1901, p. 395) mentions that a pedicle-sheath is sometimes retained to maturity in *Stropheodonta*, although its cavity is always plugged by later shell-deposits.

In the genotype *S. demissa* (Conrad), from the Hamilton (Middle Devonian) of Arkona, Ontario, Canada, the foramen is visible as a supra-apical scar (see Text-fig. 1 C).

Brachyprion Shaler

This is regarded as an incipient form of *Stropheodonta*. Kozłowski (1929, p. 96) mentions that the scar of a very small pedicle foramen may sometimes be seen at the apex of specimens of *B. subinterstrialis* Kozłowski, from the uppermost Silurian of Podolia, Poland.

Leptostrophia Hall and Clarke

In *L. canace* (Hall and Whitfield), from the Hackberry stage (Upper Devonian) of Rockford, Iowa, U.S.A., the foramen is visible as a supra-apical scar (see Text-fig. 1 D).

Pholidostrophia Hall and Clarke

Kozłowski (1929, pp. 94–5, fig. 27) describes and figures an exceedingly minute supra-apical foramen in *P. verrucosa* Kozłowski, from the Upper Silurian of Podolia, Poland. The foramen is shown, by sections, to be the mouth of a very fine canal ending internally in a cul-de-sac. The pedicle must therefore have been functional as an attachment until a quite advanced stage, when it was lost and the inner end of its passage became sealed. Kozłowski concludes that the presence of a foramen is a primitive character, since he had not seen it in Devonian species from the Eifel. Specimens of a Lower Devonian *Pholidostrophia* from New Zealand, possessing a pedicle-tube piercing the callus of the umbonal cavity, have, however, since been recorded by Shirley (1938, p. 470).

Douvillina Œhlert

A supra-apical scar, enclosed within the brephic ventral valve, may be seen in the genotype, *D. dutertrii* (Murchison), from the Devonian of Ferrones, Spain (see Text-fig. 1 E).

ORTHOTETINAE Waagen

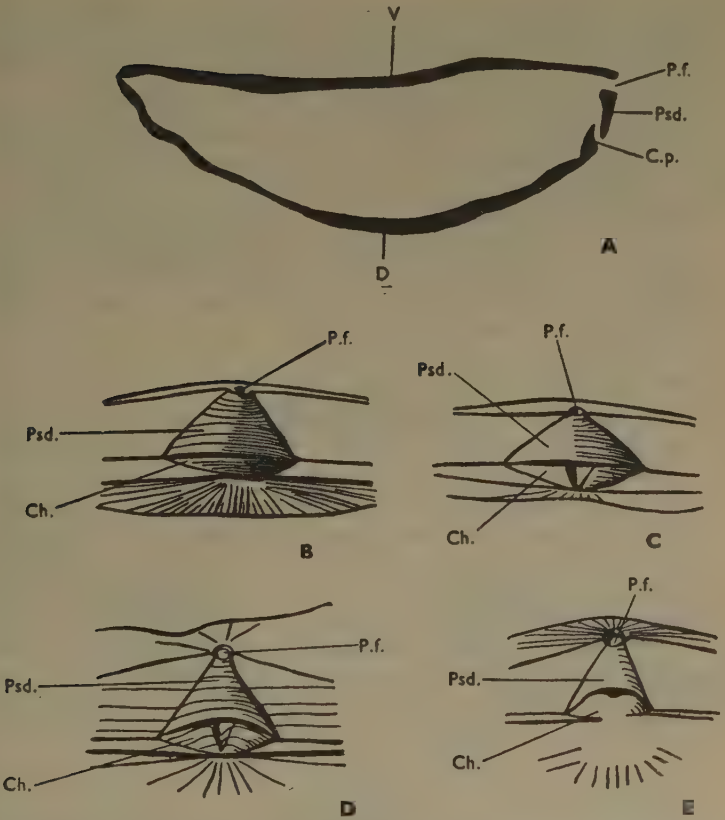
In this group, a supra-apical or apical pedicle-foramen is found in a number of genera, but it is not frequent in the Upper Palaeozoic members.

Strophomena de Blainville

The fact that the apex is perforated, except in old age, was mentioned by Hall and Clarke (1892, p. 251), in their diagnosis of the genus.

The foramen is usually present, and the scar is occasionally entirely enclosed within the brephic ventral valve, as in *S. incurvata* (Shepard) from the Upper Ordovician of North America (see Text-fig. 2 B). Sometimes, however, the foramen has been enlarged by resorption, so that it has come to be bordered dorsally by the pseudodeltidium, as in the genolectotype *S. planumbona* (Hall), also from the Upper Ordovician of North America (see Text-fig. 2 C). Here the pedicle must have survived into the neanic phase, but subsequently atrophied, since the foramen is still small and is plugged with shell-substance. On the other hand, in *S. antiquata* (Sowerby) rom the Upper Silurian of England (see Text-fig. 2 D), the foramen, though plugged, is considerably larger, and shows that the pedicle must have survived to the adult stage, while in *S. planoconvexa* (Hall), again from the Upper Ordovician of North America (see Text-fig. 2 A), the foramen is enlarged and remained open, suggesting that the pedicle was functional throughout life. Since *S. incurvata*, *S. planumbona*, and *S. planoconvexa* are found at approximately the same horizon and locality, it is evident that the pedicle might survive either to the brephic, neanic, or adult stage in related species at the same period. A similar series has been shown in *Leptaena* from the Upper Silurian of Gotland, Sweden (see Arber, 1939, text-fig. 2 A, B, C).

In *Strophomena*, the foramen is most commonly plugged after having been enlarged so as to become bordered dorsally by the pseudodeltidium. The pedicle therefore usually survived into the neanic or even early adult phase, and must have attached the animal with its ventral valve towards the sea-floor. In the brephic and early neanic stages, the ventral valve was convex, but in the adult *Strophomena* the curvature had become reversed so that the ventral was concave. The mature animal would therefore have apparently rested on the concave valve, but this is unlikely, for the opening of the shell would thus have been directed downwards into the mud. It has been suggested (see Lamont, 1934, pp. 162–3) that the majority of genera of the Strophomenacea probably lay on the convex valve, but Öpik (1930, p. 40) observes that biconvex protrematous forms such as *Platystrophia*, *Cliftonia*, and the porambonitids, may have lived with the umbo embedded downwards in the mud. Possibly



TEXT-FIG. 2

A. *Strophomena planoconvexa* (Hall) ; Hudson River group (Upper Ordovician) ; Cincinnati, Ohio, U.S.A. ; median section to show open apical foramen ; × 4. [Brit. Mus. (Nat. Hist.), BB. 6463.]

B–E. Cardinal views of umbonal region ; × 4.

B. *Strophomena incurvata* (Shepard) ; Hudson River group (Upper Ordovician) ; Cincinnati, Ohio, U.S.A. ; showing scar of supra-apical foramen entirely enclosed within brephic ventral valve. [Brit. Mus. (Nat. Hist.), B. 13504.]

C. *Strophomena planumbona* (Hall) ; Blue Limestone, Hudson River group (Upper Ordovician) ; Oxford, Cincinnati, Ohio, U.S.A. ; showing scar of apical foramen bordered dorsally by pseudodeltidium. [Brit. Mus. (Nat. Hist.), BB. 6430.]

D. *Strophomena antiquata* (Sowerby) ; Wenlock Limestone (Upper Silurian) ; Dudley, England ; showing apical foramen enlarged and plugged. [Sedg. Mus., Camb., A. 15861.]

E. *Holtedahlina sulcata* (de Verneuil) ; Hudson River group (Upper Ordovician) ; Oxford, Ohio, U.S.A. ; showing apical foramen enlarged and plugged obliquely. [Brit. Mus. (Nat. Hist.), BB. 6455.]

Ch. chilidium ; C.p. cardinal process ; D. dorsal valve ; P.f. pedicle-foramen ; Psd. pseudodeltidium ; V. ventral valve.

Strophomena also lived in a more or less upright position ; this suggestion is confirmed by the fact that, in its wavy frontal margin and deeper body-space, *Strophomena* approximates more in form to the biconvex brachiopods cited by Öpik as having lived thus, than to the concavo-convex genera which he describes as having lain horizontally.

Subgenus *Actinonema* Öpik

A minute foramen, apparently supra-apical, in the ventral valve of the subgenotype *A. orta* Öpik is described by Öpik (1930, p. 167, pl. x, figs. 131–2), and he also mentions its occurrence in *A. quintana* Öpik.

Holtedahlina Foerste

The presence of a foramen in the genotype, *H. sulcata* (de Verneuil) (see Text-fig. 2 E), was mentioned by de Verneuil in his original description of this species in 1848 (p. 350, pl. iv, fig. 4). The foramen may here be enlarged and plugged so as to form an oblique passage through the shell, thus suggesting that the pedicle survived to the early adult stage, while the animal was probably held in a more or less upright position though somewhat inclined ventrally.

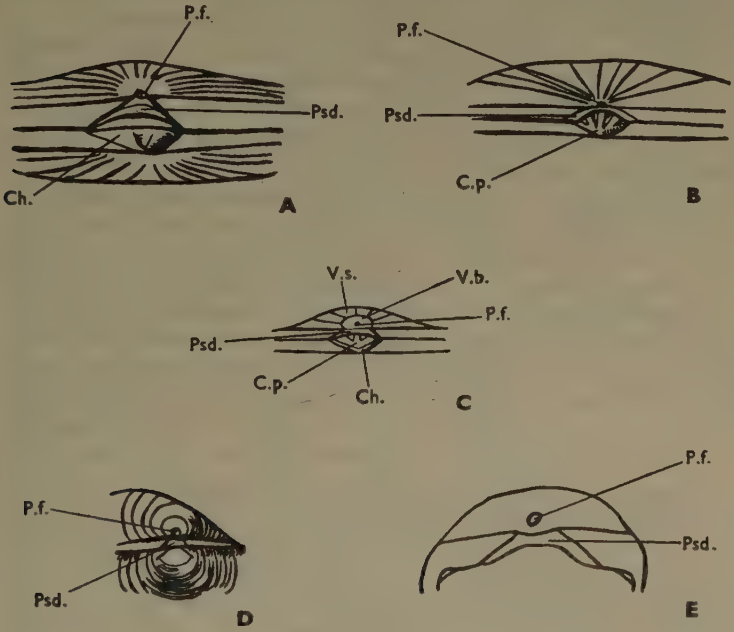
The biconvexity of the umbonal part of the shell, and the presence of a fold and sinus, again agree with the characters mentioned by Öpik as typical of those forms living with the umbo buried in the mud.

Schuchertella Girty

Beecher (1901, p. 327, pl. xvi, figs. 14–20) described and figured a series of growth-stages of *S. subplana* (Conrad) (under the name of *Orthothetes subplanus* Conrad), from the Niagara shales (Upper Silurian) of Waldron, Indiana. The youngest specimen had a hinge-length of 2·25 mm., and possessed a perforate pedicle-sheath such as occurred in *Leptaena.* This sheath did not increase in size as the rest of the shell grew, but became obscured, and according to Beecher the foramen itself finally disappeared. I have, however, observed its scar at the apex of mature specimens from Anticosti Group C (Silurian) of Anticosti, Canada (see Text-fig. 3 A).

Strophonella Hall

Beecher (1901, p. 330, pl. xvii, figs. 1–8) described and figured a series of growth-stages of *S. striata* (Hall), also from the Niagara shales of Waldron. A perforate pedicle-sheath was again found in the youngest individual, but in *S. striata* it survived throughout life. At first it was usually short and cylindrical, but it grew steadily, becoming conical and subsequently wider than high.



TEXT-FIG. 3

Cardinal views of umbonal region.

A. *Schuchertella subplana* (Conrad) ; Anticosti Group C (Silurian) ; west of Junction Cliff, Anticosti, Canada ; showing scar of apical foramen ; × 4. [Brit. Mus. (Nat. Hist.), B. 77570.]

B. *Sowerbyella sericea* (Sowerby) ; Cincinnati group (Upper Ordovician) ; Waynesville, Ohio, U.S.A. ; showing scar of apical foramen ; × 4. [Brit. Mus. (Nat. Hist.), B. 78208.]

C. *Plectodonta mariae* Kozłowski ; étage de Borszczów (Upper Silurian) ; Uście Biskupie - Chudykowce, Podolia, Poland ; showing scar of supra-apical foramen ; × 5. [Sedg. Mus., Camb., A. 15608.]

D. *Cliftonia grayae* (Davidson) ; Wenlock Shale (Upper Silurian) ; Buildwas, Shropshire, England ; showing apical foramen ; × 4. [Brit. Mus. (Nat. Hist.), B. 6483.]

E. *Christiania subquadrata* (Hall) ; Chazy (Lenoir) group (Lower Ordovician) ; ¼ m. west of Friendsville, Tennessee, U.S.A. ; detached ventral valve ; showing supra-apical foramen ; × 4. [Brit. Mus. (Nat. Hist.), B. 78729.]

Ch. chilidium ; C.p. cardinal process ; P.f. pedicle-foramen ; Psd. pseudodeltidium ; V.b. ventral brephic shell ; V.s. ventral neanic shell.

The perforation could always be seen, but Beecher concluded from the small size of the passage that the pedicle could not have performed its full function in the adult.

PLECTAMBONITIDAE Kozłowski emend. Öpik

The existence of a pedicle-foramen has been recorded in certain members of this group, but it is of less frequent occurrence than in either the Rafinesquininae or the Orthotetinae.

Öpik (1930, p. 58) mentions that it is absent in some members of his subfamily Plectambonitinae, although it is seen, for instance, in *Plectambonites planissimus* Pander emend. Öpik (see Öpik, 1933, p. 13). Öpik also mentions (1930, pp. 56, 60) that it does not occur in the subfamilies Plectellinae and Sowerbyellinae. In 1932 (p. 33), however, he described a foramen, similar to that of the other strophomenids, as typical of the genus *Ukoa* Öpik belonging to the Plectellinae. Among the Sowerbyellinae, I have observed the scar of a supra-apical or apical foramen in various Ordovician specimens of *Sowerbyella sericea* (Sowerby) (see Text-fig. 3 B), and Kozłowski (1929, pp. 114, 116, and text-fig. 36 A) has described a minute supra-apical foramen in *Plectodonta mariae* Kozłowski from the Upper Silurian of Podolia, Poland (see Text-fig. 3 C).[1] In *P. mariae*, the aperture is plugged with calcite and there is no trace of the opening of the passage on the inner surface of the valve, and Kozłowski therefore concludes that the pedicle cannot have been functional after the anabrephic stage.

A small pedicle-foramen is described in *Petroria* Wilson (Wilson, 1926, pp. 27–8), which is included by Schuchert and LeVene among the plectambonitids. Its exact systematic position appears, however, to be doubtful.

TRIPLESIIDAE Öpik

A pedicle-foramen is always present in this group (see Ulrich and Cooper, 1936, p. 333). It is usually minute and supra-apical, but it is often resorbed ventrally. Ulrich and Cooper point out that a remarkable degree of ventral resorption may be seen in some specimens of their new genus *Onychotreta*.

Text-fig. 3 D illustrates the occurrence of the foramen at the apex of the pseudodeltidium in *Cliftonia grayae* (Davidson) from the Wenlock Shale of Shropshire, England. In this species, the foramen can, by sectioning, be shown to have remained permanently open, at least in certain cases, indicating the survival of the pedicle to the adult stage. *Cliftonia* is one of the biconvex genera mentioned by Öpik as having probably lived with the umbo embedded in the mud.

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[1] I have been able to examine a set of specimens of *P. mariae*, thanks to the kindness of Professor Kozłowski in presenting them to the Sedgwick Museum in connection with this study.

DAVIDSONIINAE King

This group includes both genera which were attached by a pedicle, or free-living, and also genera which were cemented to the substratum by the ventral valve. A supra-apical pedicle-foramen may be seen in various species of *Christiania* Hall and Clarke, including *C. subquadrata* (Hall) from the Ordovician of North America (see Text-fig. 3 E). The foramen is here open to some depth, though its inner aperture has been closed, thus indicating that the pedicle probably survived to an advanced stage though not actually to maturity. A foramen is also shown in specimens of *C. subquadrata* of a later date, from the Lower Helderberg (Lower Devonian) of Tennessee, by Hall and Clarke (1892, pl. xv, fig. 33).

Leptaenisca Beecher, from the Lower Devonian, and *Davidsonia* Bouchard, from the Middle Devonian, were both cemented by the ventral valve (Hall and Clarke, 1892, pp. 300, 302), and here the pedicle was lost either completely or after the very earliest stages.

TAFFIIDAE Ulrich and Cooper

Ulrich and Cooper (1938, p. 180) mention a minute foramen at the apex of the ventral valve as a typical character of the Taffiidae, which occur in the Canadian and Chazyan formations of N. America and are the earliest known members of the Strophomenacea. The foramen is only described, however, in one species, *Toquimia kirki* Ulrich and Cooper, and has not apparently been seen in the other three genera.

INCERTAE SEDIS

A tiny foramen, similar to that of *Leptaena*, is also described by Ulrich and Cooper (1938, p. 193) in their genus *Goniotrema*, from the Upper Canadian or Chazyan, which they place in the family Strophomenidae King, though its more exact systematic position is doubtful.

III. THE PEDICLE-PASSAGE IN ONTOGENY

In the strophomenids, the delthyrial and notothyrial opening in the cardinal areas of the two valves is more or less completely covered by the pseudodeltidium and chilidium, and is also partly filled by the cardinal process. There is therefore usually no delthyrial aperture by which the pedicle could have emerged. A gap may occasionally remain, as in *Schuchertella subplana*, and Beecher (1901, pl. xvi, explanation of fig. 16) apparently suggests that in such a case the pedicle may have emerged at first through the supra-apical sheath and later through the delthyrial gap. Such a withdrawal of the pedicle from one aperture and its protrusion through another which is entirely separate, cannot, however, be visualized in development. Usually no such alternative opening exists, and so the pedicle can only have emerged through the foramen.

In species in which the foramen has been recorded, traces of it are not necessarily found in all specimens. This may be due either to accidents of preservation or to the actual loss of the pedicle at an extremely early stage. The fact that a foramen has been found in any individual of a species seems to indicate that, whenever a pedicle was present in that species, it presumably emerged by a similar supra-apical or apical passage. By analogy it may be suggested that the morphological position of the pedicle was supra-apical in related species or genera, similar in other respects, but in which the foramen has not been recorded. The fact that in the strophomenids the pedicle, when present, was primarily enclosed within the ventral valve may therefore be taken as established.

One of the difficulties discussed by Thomson (1927, p. 78) concerning the origin of the pseudodeltidium, arose from the assumption that the pedicle emerged through the delthyrium at the broader end of the pseudodeltidium, instead of at its narrower apex.

Since a pedicle appears to be universal among living brachiopod embryos, it seems probable that it occurred also in all the strophomenids. In the earliest shelled stages, it presumably emerged through a foramen enclosed within the protegulum, and in certain cases it was surmounted by a sheath, e.g. *Leptaena*, *Rafinesquina*, *Stropheodonta*, *Schuchertella*, and *Strophonella*. The pedicle then either survived and increased in size, or it atrophied at some stage, frequently so early that no trace of it remained in the adult shell. It very seldom survived throughout life, and so it may be said that in the life-history of the individual strophomenids there was a tendency towards loss of the pedicle. This loss may perhaps be correlated with the tendency of the mantle to peculiarly active deposition of calcium carbonate, which often led to the development of unwieldy shells, either greatly thickened as in many specimens of *Leptaena*, or with the hinge-line very wide in proportion to the antero-posterior length of the valves, as in some species of *Sowerbyella*.

Occasionally, when the pedicle was absent from the very earliest stages, the shell appears to have been temporarily cemented in youth by the ventral valve (e.g. *Derbya* Waagen, see Hall and Clarke, 1892, p. 263).

IV. THE PEDICLE-PASSAGE IN PHYLOGENY

Since gradual degeneration and loss of the pedicle are common in the life-histories of the individual strophomenids, it might have been expected that a similar tendency would be traceable throughout the group as a whole, so that the presence of a pedicle-foramen could be regarded as a phylogenetically primitive character. In general, however, the stratigraphical evidence does not point to such a conclusion. Although in the Rafinesquininae, the pedicle was usually functional longer in *Rafinesquina* than in the crenulate-hinged genera which succeeded it in time, yet in *Leptaena* the foramen was frequently closed in the Silurian species and open in the Carboniferous. Only among the Orthotetinae does it appear that the pedicle commonly survived longer in genera found in the Ordovician and Silurian than in the Upper Palaeozoic. In the other "subfamilies" it appears that the length of life of the pedicle in a particular species bears no relation to the "primitive" or "derived" position of that species and genus in the evolution of the group, or to the horizon at which it occurs. As mentioned earlier, in approximately contemporary species of the same genus from the same area, the pedicle may survive respectively into the brephic or neanic stages or throughout life; while at one period the Davidsoniinae exhibit a genus attached by a pedicle until it almost reaches maturity, and another genus in which from the earliest stages the pedicle has been lost and the shell has been cemented by the ventral valve. It remains, however, possible that some of the variations within the species of a genus, or the individuals of a species, might be correlated with minor differences in environmental conditions.

A pedicle-foramen is often, but not always, present among the Canadian and Chazyan "pro-strophomenoids" of Ulrich and Cooper (1938, p. 13), which possess the internal characters of the Orthacea, but the pseudopunctate shell-structure and the pseudodeltidium of the Strophomenacea. The length of life of the pedicle was therefore variable even among the earliest known, and supposedly primitive, members of the Strophomenacea, and, throughout the whole group, degeneration and loss of the pedicle appears to be a sporadic character of certain genera, species, or even individuals, rather than to have any evolutionary significance.

V. CONCLUSIONS

It is suggested that the morphological position of the pedicle throughout the young stages of the strophomenid brachiopods is supra-apical, as in *Leptaena*. The primary relation of the shell to the pedicle is therefore apparently homologous in the various subdivisions of the "family", indicating that from the standpoint of development the strophomenids may be regarded as a homogeneous group.

Although the position of the pedicle is of significance in phylogeny, its function can have been of little biological importance. It seldom survived to maturity, and since it disappeared at varying times among individuals apparently similar in other respects, it cannot be supposed that the mode of life of the animal was much affected by the presence or absence of an attachment.

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REVIEWS

REPORT UPON THE MINING INDUSTRY OF MALAYA. By SIR LEWIS LEIGH FERMOR. pp. xv + 240, with two maps and seven figures. Federated Malay States Government Press, Kuala Lumpur. $2·50 or 6*s*.

This report, with a topographical and a geological map published by the Survey and Geological Survey Departments, is the result of a visit to Malaya at the request of the Secretary of State for the Colonies in 1938, extending from March until November, when unfortunately the author's work was interrupted by serious illness which necessitated an immediate return to London. Notwithstanding this interruption the report contains a wonderful mass of valuable information and is remarkably free from errors of fact, indeed only one of importance has been detected. The author says on p. 42 that gold was recovered in Malacca for the first time in 1938 ; but there are old gold workings near Mt. Ophir that were opened many years ago. The report will be of value chiefly to those interested in mineral production and mining administration, but to geologists there is at least one very interesting general topic that can appropriately be noticed here, namely the functions of a Geological Survey Department and a Mines Department in relation to one another. Space does not admit discussing this in detail and the author himself summarizes the matter by saying that a Mines Department should be responsible for the safety of the miners and the Geological Survey for the safety of the minerals. In Malaya, as in India, the two departments are distinct and the harmonious relations that have always existed between the two make any change unnecessary. In the Netherlands East Indies, however, there is a different administrative structure. One department, the *Mijnbouw*, comprises several divisions which carry out not only the work of a Geological Survey and a Mines Department, but also Government mining and prospecting, the whole being controlled by a *Hoofd van den Dienst van den Mijnbouw*, who occupies a position which perhaps the mining community of Malaya had in mind when they asked for a " Mining Adviser ".

The Colonial Office was fortunate in obtaining so experienced an authority as Sir Lewis Fermor to prepare this report and the reviewer takes this opportunity of gratefully acknowledging his tribute to the early geological work in Malaya.

J. B. S.

EARTHQUAKES AND OTHER EARTH MOVEMENTS. By J. MILNE. Seventh edition. Revised and re-written by A. W. LEE. Kegan Paul, Trench, Trubner and Co., Ltd., 1939. Price 10s. 6d.

Milne's "Earthquakes"—for many years since its first appearance in 1883, a standard work—has long been out of date, and Dr. Lee's revision is virtually a new book. The evidence regarding the nature and travel of elastic waves through the earth's interior is most lucidly set forth, and geologists who may well be bewildered by the flood of recent seismological literature will here find an admirable statement of the present outlook of the science, and a restrained discussion of what may be deduced of the state, arrangement, and composition of the materials of the interior. The account of the permanent displacements which have accompanied great earthquakes is, however, disappointingly meagre.

The rapidly accumulating data relating to deep focus earthquakes, i.e. those originating at depths of from 50 to 700 kilometres, are of the greatest interest. The deep focus earthquakes give evidence of shearing movements. In the circum-Pacific regions their epicentres lie on certain planes inclined downwards towards the continents, and up which the continental masses are jerking. The volcanoes are commonly situated where the planes of weakness are 100 kilometres deep. Similar thrust planes have long been postulated in the "wedge" and other theories of diastrophism, but their continuance to depths of hundreds of kilometres presents an intriguing problem. One of the minor services of seismology to geology is the precise definition of that hitherto unsatisfactory term the "crust" of the earth. The crust comprises the sedimentary, granitic, and basaltic (rather unfortunately termed "intermediate") layers, and the position of its base, normally about 30 kilometres down, can be determined from a study of "near" earthquakes.

L. H.

GEOLOGICAL MAGAZINE

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The Yorkshire Dogger

I. The Coastal Region

By R. H. Rastall and J. E. Hemingway

IN an earlier paper in this magazine it was stated that we were then engaged on a general study of the Yorkshire Dogger. This subject has proved to be so complicated and far-reaching that it is not possible to present all the results in a single paper of any reasonable length. Moreover, as will be seen later, owing to noteworthy local changes in lithology of the Dogger and to its stratigraphical relations certain very definite types can be recognized, characteristic of large and well-marked areas. This feature lends itself readily to serial publication and the present paper deals with the most accessible, if not perhaps the most interesting area, namely the coast from Peak (Ravenscar) to Saltburn. This part of the outcrop is referred to for convenience as the coastal Dogger.

Historical Introduction

In North-East Yorkshire the term " dogger " has long been applied by alum workers and others to any rounded mass of dense tough rock irrespective of its composition, origin, or geological horizon. Concretionary masses from the Lias or spheroidally weathering ironstones and sandstones were and are still referred to by local people as " doggers ". Apparently limitation in the use of the word did not occur until the early nineteenth century, for in Charlton's *History of Whitby* (1779) the Dogger is referred to, though not by name ; " . . . above the allum-mine we meet a ſolid body of ironstone, much heavier than the allum-mine ; and above that is a ſtratum of doggers." By 1817 the term was used with greater exactness, although not reserved exclusively for the group of rocks to which it refers to-day. Thus the Rev. George Young in his *History of Whitby* (1817) writes, " On the top of the aluminous schistus rests a stratum of hard compact stone. . . . The workmen call it *dogger*, a name which they also give to the cement-stone. . . ." A short description follows.

In 1822, in conjunction with John Bird, Young published the first of two editions of his *Geological Survey of the Yorkshire Coast*, a monumental pioneer work of painstaking labour and entirely original investigation. Although not free from errors and overshadowed a few years later by John Phillips's more academic *Illustrations of the Geology of Yorkshire: the Yorkshire Coast*, Young's work provided the first formulated description of the Jurassic rocks of Yorkshire and upon it all subsequent work was based. In broad outlines the stratigraphical succession and the fauna were described and although the accompanying map is useless it is obvious that much of North-East Yorkshire was visited. Young's detailed description of the Dogger is of a high standard and far excels those of many subsequent authors. He noted its variable character " in some places a coarse sandstone . . . in others a coarse breccia . . . sometimes so calcareous as to effervesce with acids, sometimes an argillaceous sandstone, sometimes rather siliceous and not infrequently a kind of clay ironstone ". Young also observed " the imbedded fragments " in the Dogger and pointed out that although " some have the appearance of concretions . . . most of them seem to have belonged to other rocks ". Further descriptions of detailed sections, of the weathering of the Dogger, and of the presence of galena and blende within the rock are followed by the final and perhaps most surprising observation : " . . . in the hills fronting the plains of Cleveland, as at Guisborough, Ayton, Carlton, etc., there seems to be no bed corresponding with it [i.e. the Dogger] : or perhaps it may be more correct to say that in these hills it loses its conglomerate character and passes into a common sandstone." This very early appreciation of the absence of Dogger in western Cleveland, together with the accuracy of his descriptions, the high standard of which was not attained, let alone surpassed, for the next eighty years, testifies to the excellence of Young's observations.

In the first two editions of his *Illustrations* (1829 and 1835) Phillips refers to the " irony dogger bed . . . a very singular layer of inconstant appearance and varying substance ". He recorded the occurrence of pebbles and although most of his identifications of these have not subsequently been confirmed it may be noted that he considered some were probably derived from the Lias. In the third edition (1875) this brief account of the Dogger is essentially unaltered.

About 1852 the Dogger was worked as an ironstone and in 1860 Watson noted its variable thickness and iron content in the Esk valley. He commented on its high silica content and observed that it was used to mix with more argillaceous ores since it fluxed more easily.

In 1861 was published the *Geological Treatise on the district of Cleveland in North Yorkshire, its ferruginous deposits, Lias and Oolites, etc.*, by Bewick. It is mainly devoted to the distribution of ironstone in Cleveland,[1] and the Dogger or Top Seam as it was known to the miners is described, though only in general terms, with no measured sections. This work represents the first description of the Dogger in Eskdale and the radial Cleveland valleys, with which it is apparent Bewick was closely familiar. He comments on its varying thickness, occasional oolitic structure, and rapid lithological variation. He emphasized the deceptive ferruginous appearance of the weathered crust, which may, he states, contain up to 40 per cent of iron " whilst the core . . . is an arenaceous mass of no value whatsoever ", and pointed out that when calcined " there was no detecting its inferiority (as an ironstone) until tried in the furnace ".

Hudleston described the Dogger and its fauna, particularly at Blea Wyke Point, in 1874. He noted the phosphatic content of the pebbles, but stated that " those who took these things for pebbles were mistaken ". He also considered that the iron content of the matrix, which was recognized as chiefly carbonate, was " a true replacement of lime by iron " by downward percolation.

Tate and Blake in 1876 discussed the relations of the Lias and Inferior Oolite. Although little attention was paid to lithology, sections both on the coast and inland were measured and fauna collected with an accuracy far exceeding the subsequent descriptions by the officers of the Geological Survey. Later, in 1891, Blake stated that the pebbles were concretions of phosphate precipitated by the dead bodies of animals killed by rapid change of environment.

During the 1870's the whole of North-East Yorkshire was mapped by the Geological Survey, the descriptive Memoirs being published between 1881 and 1888. Of these *The Geology of North Cleveland* (1888) and *The Geology of the Country between Whitby and Scarborough* (1882 ; second edition 1915) include the coastal area of Dogger described in this paper. All the Memoirs were summarized by Fox-Strangways in *The Jurassic Rocks of Britain, I: Yorkshire*, a two volume monograph published in 1892. Although most of the Dogger was mapped by Barrow, Fox-Strangways was responsible for a part of this work, and Clement Reid mapped the Cleveland dales. It is perhaps this diversity of investigation and authorship, together with the immature state of sedimentary petrology at that time, which caused the incoherence and even inaccuracy of the descriptions of the Dogger. Although many of the more accessible exposures were described, little attention was paid to the petrology of the rocks or to the distribution and field relationships of the several lithological types.

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[1] The term Cleveland is here used in the broader and more recent sense to include all that moorland region north of the Tabular Hills. In the strict sense Cleveland is north of the River Esk, the intervening district being known as Blackamoor, a term now long fallen into disuse.

In 1905 the senior author (R. H. R.) described the Blea Wyke Beds and the Dogger of North-East Yorkshire, particularly the coastal region. The fauna was described in detail and attention was drawn to the frequent occurrence of Lower Estuarine washouts in the Dogger. The derived origin of the pebbles was pointed out and emphasis laid on the occurrence of rolled fossil fragments.

Further washouts were described in 1923 by Tonks, who confirmed the derived origin of the pebbles. He also briefly described the petrology of the Dogger and regarded the state of the matrix as due to metasomatic replacement of lime by iron.

A notable contribution was made in 1932 by Macmillan who recognized the existence of high Whitbian and Yeovilian horizons in the central Cleveland valleys and who was also able to date the Dogger of Glaisdale and Mulgrave as of upper *opalinum* (Lower Aalenian) age. Previous to this work all marine deposits between the Alum Shales and the Lower Estuarine Series, in localities other than Blea Wyke, had been collectively grouped as Dogger.

In 1934 Black discussed in detail the sedimentation of the Dogger and associated beds, particularly in North and North-West Cleveland. He demonstrated the changes that this region had undergone in Yeovilian and Aalenian times and recorded the presence of Upper Aalenian ammonites in these districts.

References to the Dogger in the volumes of the "Special Reports on the Mineral Resources of Great Britain" (*Mem. Geol. Surv.*) descriptive of iron ores relate almost entirely to its development in Western Cleveland and Rosedale. We hope to refer to these in later papers dealing with those areas, now in active preparation.

FIELD DESCRIPTIONS

On the west side of the Peak Fault the Dogger is well exposed for two miles in the disused alum shale quarries in the steep hillside of Stoupe Brow and in the adjacent beck sections. This series of exposures alone furnishes an excellent example of the variability of the coast Dogger both in thickness and, within limits, of lithology. A few inches of Dogger are exposed in a spring 350 yards west of the fault, but in the two quarries known as Peak Alum Works it may be examined continuously for scores of yards. The eastern of these is now Ravenscar Brick Works. At its eastern end the following section was measured.

	ft.	in.
Lower Estuarine series		
Massive sandstone	10	0
Sandy shales	10	0
Dogger		
Sideritic sandstone with three prominent siderite-mudstone bands	1	3
Sideritic sandstone	2	0
Alum Shale		

Immediately to the west this section is cut out by a small washout of Lower Estuarine[1] sandstone to the west of which is a better exposure. Here the upper bed of the Dogger is much less sandy, being represented by rows of siderite-mudstone nodules, oolitic in places, and by sandy shales.

	ft.	in.
Dogger.		
Siderite-mudstones variably sandy and oolitic, in sandy shales	1	2
Pebbly sandstone		4
Sideritic sandstone with pebbly base resting irregularly on	2	3
Upper Lias		
Chocolate mudstone	1	3
Shale with pebbles	1	0

The pebbly base of the Dogger is characteristic of the whole of the coastal region and of much of North-East Yorkshire. The pebbles are present either as an individual bed or more usually as an integral part of the massive Dogger. They are also found distributed sporadically through the rock and more rarely, as in this case, in beds at higher horizons.

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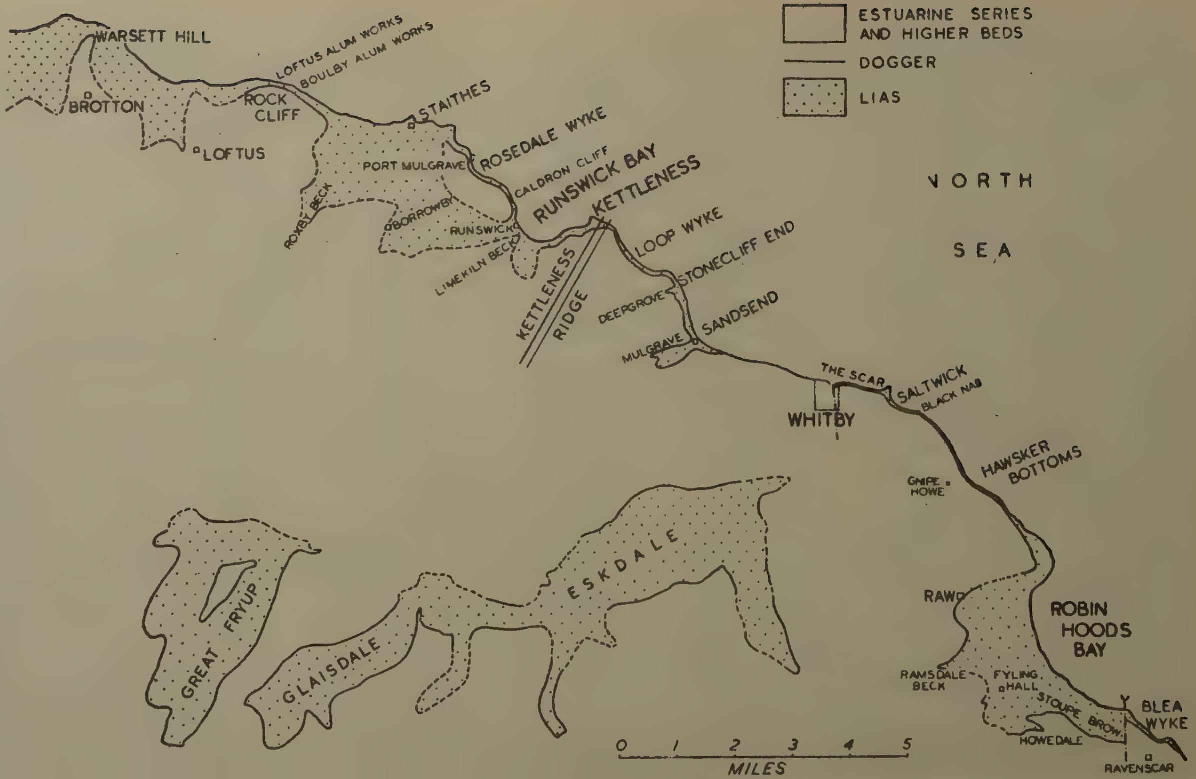
[1] Throughout this work we shall have frequent occasion to employ the term "Estuarine" in the stratigraphical sense. It must not be supposed, however, that we accept the literal implication of this unfortunate word, a major disaster of Yorkshire geology. It has been conclusively shown by Black that the middle Jurassic of North Yorkshire affords a typical example of delta formation with coals, seat-earths, marine bands, and washouts: in fact, a miniature coalfield.



[illegible] Localities and [illegible] outcrop of Dogger in the coastal region.

The chocolate-coloured mudstone, an earthy siderite mudstone, is constantly associated with the coast Dogger. It is either overlain immediately by the massive Dogger or separated from it by a small thickness of shale, and occurs either as a row of nodules or as a continuous bed. It is usually unfossiliferous and its age has long been in doubt, some writers associating it with the Alum Shale and others with the Dogger. The discovery of a lamellibranch-ammonite fauna in this bed at Kettleness to the north-west has, however, proved its Whitbian-Yeovilian age (see p. 189).

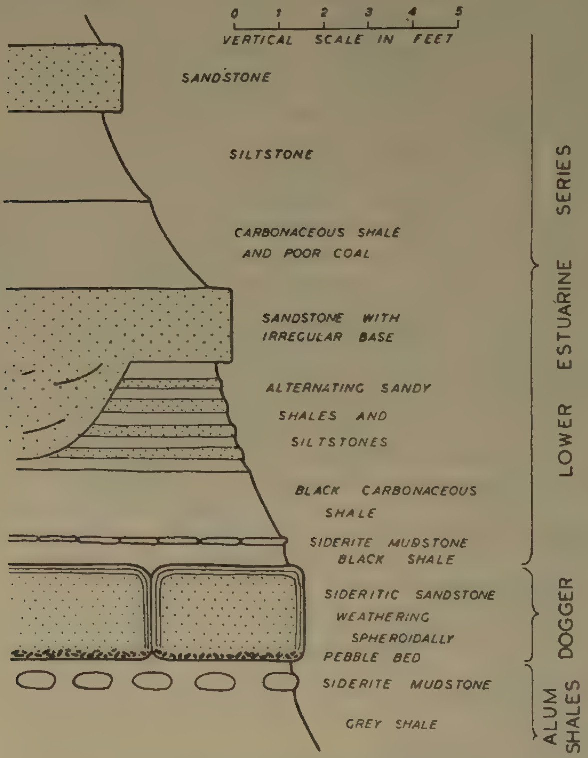
The more massive Dogger sandstone increases in thickness above the kilns in Ravenscar Brick Works and in the middle of the adjacent Peak Alum Works attains 4 ft. 6 in. From this point it thins rapidly to a 10 in. bed, pebbly throughout and in the western end of the quarry this pebble bed is even thinner. In the Peak Alum Works the Dogger is lithologically outstanding, a blue sideritic rock, variably sandy, with strong vertical jointing and an upper surface weathered into conical mounds, the irregularities between being filled with pebbles in a shaly matrix, and the whole overlain by Estuarine sandstone.

For 1,300 yards the Dogger is hidden, but in Stoupe Brow Alum Works it is still represented by a pebble bed.

	ft.	in.
Lower Estuarine Series		
Shale	10	0
Flaggy sandstone and shale	1	4
Shale		6
Massive carbonaceous sandstone	1	0
Dogger		
Pebble bed 12–15 in.	1	2
Upper Lias		
Chocolate mudstone	1	4
Alum Shale	—	

About 150 yards south-west of Howdale School the Dogger is represented by a sideritic sandstone 2 ft. 2 in. thick with the usual pebbly base and in this character it can be easily traced round the small valley of Howdale, gradually increasing in thickness (Text-fig. 2). From here the outcrop is hidden under Boulder Clay and the Dogger is exposed only sporadically, as in a beck section above Pretty House, near Fyling Hall Station, where it is 12 feet thick. It may also be seen in the beck near Ramsdale Mill; in a roadside gutter at Sledgate, by the road leading to Fyling Hall; and in a beck section in the village of Raw, where it is only 1 foot thick.

From this point the outcrop swings beneath the Boulder Clay to the coast and the Dogger is well exposed by the side of the cliff path known as Jackass Trod or Sawdon's Road, near Hawsker Bottoms.[1]



TEXT-FIG. 2.—Typical Upper Lias—Inferior Oolite contact as seen in Howdale.

	ft.	in.
Dogger		
Sideritic sandstone with basal pebble bed	5	3
Upper Lias		
Chocolate mudstone	1	0
Alum Shale	—	

The Dogger is then continuously exposed in the cliff face as far as Whitby, a distance of three miles, except where it is cut out by Estuarine washouts. For the most part it is entirely inaccessible although the lithology and the thickness of the bed can be ascertained from the abundant large fallen blocks. Below Gnipe Howe the siderite content increases to form a strikingly banded rock, this banding being controlled by the distribution of the sandy fraction.

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[1] Jackass Trod is the original name of the old smuggler's track up the cliff, which in modern literature is expurgated to " Donkey Path ".

At Saltwick the Dogger is again accessible.

	ft.	in.
Lower Estuarine Series		
Alternations of sandstone, grey clay, and impure coal	—	
Dogger		
Sideritic sandstone with pebbly base and occasional pebbles throughout	2	0
Upper Lias		
Chocolate mudstone	1	9
Alum Shale	—	

Midway between Saltwick and Whitby the Dogger dips to beach level in the core of the Whitby syncline and forms a prominent reef at the cliff-foot, which is in part cut out by an Estuarine washout. The Dogger is here only 16 inches thick, a tough sandy siderite rock, grey when fresh and pierced by the casts of roots of Estuarine plants, which pass through it into the Alum Shale below. This remarkable rock will be described in detail later.

At this point large worm tubes descend from the Dogger into the Alum Shale. They are U-shaped, the tube being circular in cross-section and about ½ inch in diameter. The arms of the tube, which are slickensided, are usually about ½ inch apart at the point at which they descend from the base of the Dogger. The tubes themselves are infilled with the typical sideritic sandstone of the Dogger. Not only are these structures found at the base of the Dogger, for at Black Nab, south-east of Saltwick, they may be seen piercing the upper surface. A derelict quay originally constructed for the shipping of alum shows the typical key-hole structure on the weathered surfaces of the blocks of Dogger of which it is built. These worm burrows bear a strong resemblance to *Arenicolites statheri* and to *Arenicoloides*.

At the Spa Ladder on Whitby East Pier the Dogger, here 40 feet O.D., is 2 ft. 6 in. thick, and is deeply weathered and overlain by shales with rows of small ironstone nodules. From this point the outcrop swings south into Whitby harbour, dipping steadily to river level.

The Whitby Fault, with a downthrow of 200 feet to the west, throws the Dogger below sea-level for two miles. It reappears by the roadside near East Row, Sandsend, where the usual sideritic sandstone is overlain by a black oolite. This has already been described by the authors (Rastall and Hemingway, 1939*a*).

In the vicinity of Sandsend the Dogger is well exposed. In Mulgrave Woods it may be examined in many places and at Rock Head Alum Works, immediately north of Rock Head Farm, the following deeply weathered section was measured :—

	ft.	in.
Lower Estuarine Series		
Black shale	2	0
Dogger		
Soft, brown ferruginous sandstone slightly fossiliferous	3	0
Rotten stone		5
Soft ferruginous sandstone, very fossiliferous and with occasional derived pebbles	2	9
Upper Lias		
Alum Shale	—	

The subdivision of the Dogger into two distinct blocks, of which the lower is highly fossiliferous, is characteristic of the Mulgrave and Sandsend district. This is the only area west of the Peak Fault where the Dogger yields a satisfactory fauna (Macmillan, 1932). It consists primarily of lamellibranchs, but included an outer whorl of a large *Leioceras* of the upper *opalinum* zone (Lower Aalenian) and fragments and one complete ammonite of undoubted Yeovilian age. The ornament of these fossils was slightly abraded and the possibility of the Dogger being of post-upper *opalinum* age (i.e. upper Aalenian) and not upper *opalinum*, as claimed by Macmillan, should not be overlooked.

The two-fold division of the Dogger continues into the several alum works immediately north of Sandsend, the separation of the two individual blocks becoming here more distinct with the development of thin shales with rows of oolitic siderite-mudstone nodules between them. The break is further emphasized by the presence, particularly near Sandsend, of derived pebbles on the irregular upper surface of the lower block.

When traced farther north the upper block becomes, above the railway, increasingly ferruginous in character with the development of siderite-mudstone lenses within it. This apparently proceeds with a concomitant decrease in the amount of sandy detritus, a feature also noticed in Peak Brick Works, until in Deepgrove Alum Works the upper block is no longer present as an individual bed but is represented by thin siderite-mudstones separated by a sandy shale. This facies change can be traced with such exactness and continuity that there is no possibility of mistaken correlation. Two further sections in this vicinity, at Stonecliff End near the south-east end of Kettleness railway tunnel and in the steep gully of Overdale, expose a thick pebble bed in the upper part of the Dogger together with sandstones of apparently only local development (Text-fig. 3).

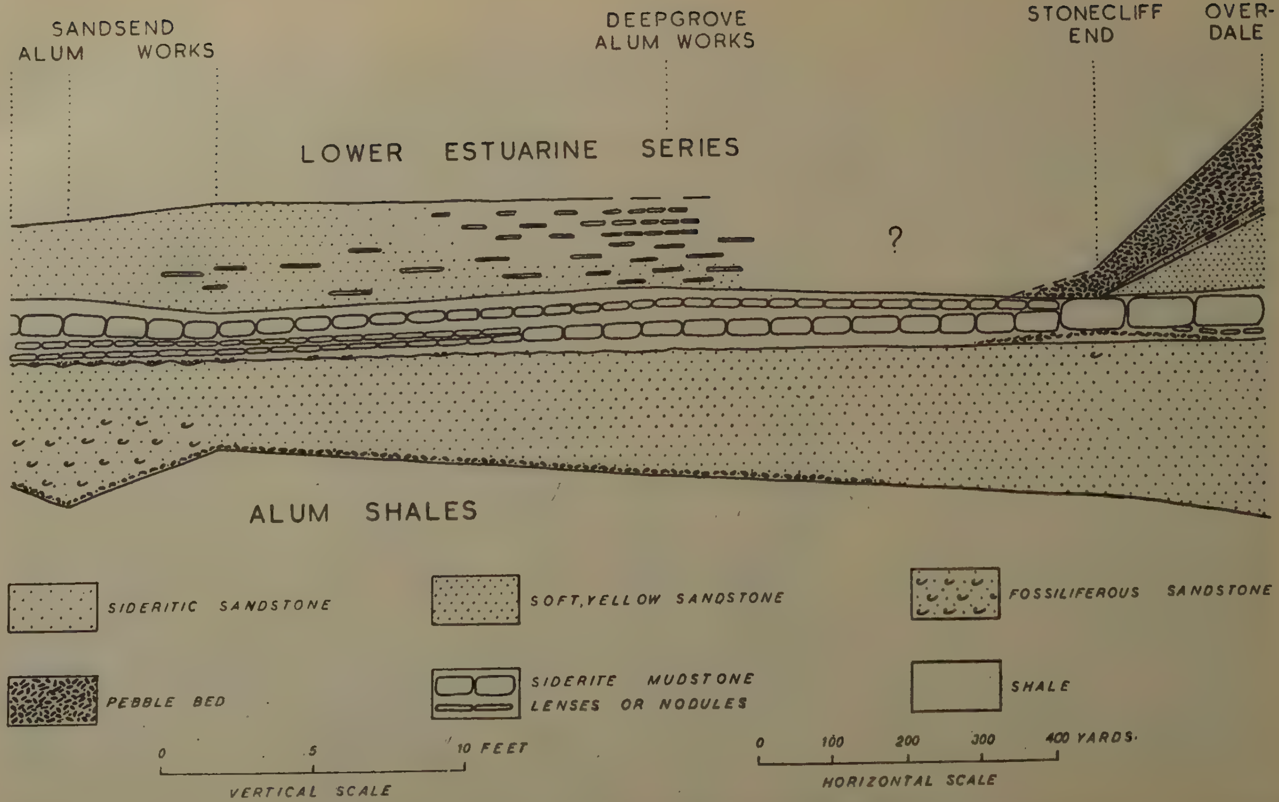
For a mile to the north-west the Dogger is inaccessible, though easily visible in the steep cliff face. In Loop Wyke, near the north-west end of Kettleness tunnel it is again accessible and the following section was measured :—

	ft.	in.
Lower Estuarine Series		
Massive sandstone		—
Dogger		
Massive sideritic sandstone with prominent lenses of siderite-mudstone	6	4
Sandy shale with pebbles		4
Concretionary siderite-mudstone		3
Pebble bed, 4–6 inches		5
Massive siderite-mudstone	1	2
Shale with pebbles		8
Upper Lias		
Chocolate mudstone		8
Occasional pebbles		—
Alum Shale with cement-stone nodules seen	10	0

The occurrence of rows of siderite-mudstone nodules with pebbles below the Dogger is an unusual feature. These nodules are quite different from the earthy chocolate mudstones and probably belong to a higher zone, the break being marked by the shale with pebbles. No fossils, however, were obtained from them.

Within 400 yards the Dogger changes completely, and at the north end of that part of the cliff known as Holmes Grove, below the south end of the shorter railway tunnel, the following was measured :—

	ft.	in.
Lower Estuarine Series		
Massive current-bedded sandstone with casts of logs and pebbly base	20	0
Well-bedded grey sandy clay with one large sandstone lenticle	4	0
Dogger		
Dense sandy siderite rock with few pebbles at top		5
Pebble bed: lower part in shale matrix, upper part in oolitic mudstone	1	0
Upper Lias		
Chocolate mudstone		10
Alum Shale		—



Text-fig. 3.—Lateral variation of the Dogger north of Sandsend.

The pebble bed persists for a further half mile, and it may be traced continuously through Kettleness Alum Works and by the road leading to the shore. In the former place a section showed :—

	ft.	in.
Lower Estuarine series		
Yellow sandstone : upper part a washout, lower part massive but well bedded	40	0
Clays and thin sandstones		10
Dogger		
Pebble bed in sideritic and shaly matrix		4
Lias		
Massive chocolate mudstone	1	2
Alum Shale		—

From the chocolate mudstone in the above section a poorly preserved lamellibranch and ammonite fauna was obtained, which served to determine the age of this widely recognized deposit. The ammonites were identified by Dr. L. F. Spath and the lamellibranchs by Dr. L. R. Cox, both of the British Museum (Natural History), to whom we tender our best thanks. Two fragmentary ammonites were found belonging to different horizons, so that the older is probably derived. This is a representative of the genus *Crassicoeloceras* (*Coeloceras crassum* group), and belongs to the *bifrons* zone, most probably to the lower part. The other is an indeterminate Harpoceratid suggestive of the genus *Haugia* and seems to belong to the *Grammoceras* beds (*variabilis* or *striatulum* zone). The lamellibranchs, which are more abundant, belong to two species *Gresslya donaciformis* (Phillips) and *Pleuromya elegans* (Phillips).[1] The Harpoceratid ammonite fragment in particular serves to date the mudstone as lying on about the border-line between Whitbian and Yeovilian. It is definitely of Upper Liassic age and should not therefore be grouped with the Dogger.

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[1] Dr. L. R. Cox writes : "Note on *Pleuromya elegans* (Phillips) : This species, the type of which was said to come from the 'Upper Lias Shale', was figured by Phillips (*Geol. Yorks.*, 1829, pl. xii, fig. 9) under the generic name *Sanguinolaria*. Tate (in Tate and Blake, *Yorkshire Lias*, 1876, p. 407) remarks that he had seen no examples of the species, and the name has not since appeared in the literature. In the same work (loc. cit., p. 407, pl. xvi, fig. 9) Tate figures the type of *Pleuromya contracta* (Simpson, sub *Amphidesma*), from the "Upper Lias, Whitby". This specimen, which I examined in the Whitby Museum in 1938, seems to be a distorted specimen of *P. elegans*. A less distorted specimen, identified as *Pleuromya contracta* but agreeing well with Phillips's figure of *P. elegans*, except in the slightly less anterior position of the umbones, is on another tablet (no. 714) in the Whitby Museum. Hence it seems most probable that *P. contracta* should be regarded as a synonym of *P. elegans* (the type of which, unfortunately, is no longer extant). The oblique posterior truncation of the species is characteristic ; it bears some resemblance to a *Cardinia*."

The section by the side of the track to the beach is similar to that in Kettleness Alum Works and in the matrix of the pebble bed occur small aggregates of crystalline zinc-blende. Between this point and Cat Beck, in a distance of 250 yards, the Dogger increases to almost 15 feet in thickness. This section, principally made up of oolites, has already been recorded (Rastall and Hemingway, 1939*a*).

From Cat Beck, Kettleness, the Dogger may be traced along the cliff face to Claymoor. It is next exposed, under slipping boulder clay and almost at sea-level, in the middle of Runswick Bay, where the following section was measured :—

	ft.	in.
Lower Estuarine series		
Dark grey shales	3	0
Dogger		
Green chamositic sandstone	1	6
Siderite-mudstone		11
Shale		8
Alternations of green sandstones and siderite-mudstone in 4 in. beds, capped by an oolitic siderite-mudstone	about 2	6
Upper Lias		
Alum Shale		—

The junction of the Lias and the Dogger was not exposed. An outstanding feature was the close association of the siderite-mudstone and the chamositic rocks, each forming an integral part of the whole block and not forming separate beds.

The Dogger may be traced high in the cliff above Runswick village, but only the upper beds can be seen here, deeply weathered at the foot of Lingrow End, a vertical crag of massive Estuarine sandstone. At the most northerly point where the adjacent Caldron Cliff is accessible, the following complete section was exposed :—

	ft.	in.
Lower Estuarine Series		
Massive white and yellow sandstone	25	0
Dogger		
Green chamositic sandstone with lenses of siderite mudstone	8	0
Thin shales and sandstone	1	8
Siderite-mudstone		4
Grey clay with thin wisps of whitish sandstone		9
Alternations of siderite-mudstone and greenish-brown sandstone		9
Fossiliferous pebble bed in weathered greenish-brown sandstone		3
Upper Lias		
Chocolate mudstone		3
Alum Shale		—

In the pebble bed were found waterworn *Trigonia*, *Gresslya*, and coral fragments.

This sequence may be traced through Wrack Hills, a part of Lingrow Cliffs, where an impersistent 1 ft. sideritic sandstone occurs in the green sandstone for a short distance. Below High Lingrow the cliffs are vertical and the Dogger is completely inaccessible, although it would appear from examination with binoculars and from recent cliff falls to maintain the Runswick sequence.

In the middle of Rosedale Wyke[1] the Lias-Oolite junction is exposed near Lingrow Keld. Only about 5 feet of shales with concretionary siderite mudstones are seen above the Alum Shales, the higher beds of the Dogger being cut out by an Estuarine washout. This is doubtless the "freestone baulk" of the ironstone miners (Fox-Strangways, 1892). This section is now partially hidden by a recent heavy fall of massive sandstone. Above Port Mulgrave several drifts have been made into the Dogger, to obtain ironstone, and one of these provides a clear section :—

	ft.	in.
Lower Estuarine Series		
Dark shales with coal passing gradually into	10	0
Thin irregular flags with shaly intercalations and siderite-mudstone lenses (forming roof of adit)	6	0
Dogger		
Massive siderite-mudstone, variably oolitic (12 to 16 inches)	1	2
Green chamosite-oolite	3	0
Upper Lias		
Chocolate mudstone		4
Alum Shale		—

This section is typical of Port Mulgrave and the coast northwestwards for a farther half mile. Midway between Port Mulgrave and Staithes the outcrop of the Dogger swings inland and for two miles disappears beneath boulder clay. Its position may be approximately followed near Borrowby, where the drift cover is thin, and in Lowhouse Gill and along the south side of Roxby Beck the Lias-Oolite junction is exposed. In these sections the Dogger is absent and Lower Estuarine washout sandstones rest directly on Yeovilian shales. These exposures will be referred to more fully in a later paper.

In Rockcliff the Dogger attains a height of more than 500 feet O.D., and it can be traced through the several alum works in its seaward face. In Boulby Alum Works, the most easterly of these, the Dogger first appears as an oolitic siderite-mudstone up to 22 inches thick overlain by 10 feet of dark shales with similar mudstone nodules. Within a hundred yards, just before it is cut out by an Estuarine washout, the lithology of the main bed has completely changed to a brown rather earthy sandstone with shaly lenses. The Dogger is fully exposed between these two points and the change may be continuously traced. Nowhere can the rapid lithological change so typical of the Dogger be better or more conclusively demonstrated. It serves also to show the inadvisability of correlating individual beds of the coast Dogger even over short distances. When next seen, farther west in Boulby Alum Works, the Dogger is much thicker. The following section was measured on a small bluff, since collapsed, near the mouth of a derelict ironstone adit.

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[1] This small bay, Rosedale Wyke, which shelters the derelict Port Mulgrave, should not be confused with the valley of Rosedale 14 miles to the S.S.W. Both localities were formerly closely associated with ironstone mining.

	ft.	in.
Lower Estuarine series		
Coarse brown sandstone, with casts of logs (base of washout)	8	0
Dogger		
Splintery oolitic siderite-mudstone		9
Soft brown oolitic ironstone, with white weathering ooliths. Frequent small pebbles increasing in number downwards	2	7
Earthy ironstone with large black polished pebbles		2
Shale with abundant large pebbles; upper and lower surfaces irregular, 1–3 inches		2
Lias		
Chocolate mudstone 4–8 inches		6
Alum Shale	—	

Still farther west in the same quarry an Estuarine washout cuts almost entirely through the Dogger leaving only a thin pebble bed.

The western end of Boulby Alum Works is bounded by a landslip which completely hides the solid rocks and which serves to separate Boulby from Loftus Alum Works. The Lias-Oolite junction in the latter quarry has already been described (Black, 1934), and the following succession is summarized from this paper :—

	ft.	in.
Lower Estuarine Series		
Grey shales with impure coal	5	0
Murchisonae Beds		
Ferruginous shales, silty and unfossiliferous	7	0
Shales with rows of siderite-mudstone nodules with *Ludwigia*	3	9
Pebble bed		3
Of Doubtful Age		
Shale		6
Chocolate mudstones	1	0
Whitbian		
Alum Shale	—	

It is now known from evidence at Kettleness (p. 189) that the chocolate mudstone is of Whitbian-Yeovilian age.

This section, as has been pointed out (Black, 1934), is characteristic of the Lias-Oolite junction over much of Cleveland to the west and south-west. Similar sections in natural exposures, but particularly in old alum works, may also be seen in the Saltburn and Guisborough districts. In these exposures the Dogger is not represented either as a sideritic sandstone or a sandy oolite and is believed to be absent.

In two localities, however, the Dogger is known to occur. On Warsett Hill, near Brotton, small unsatisfactory exposures show :—

	ft.	in.
Weathered oolitic siderite-mudstone with ½ in. pebbles . .	1	0
Calcareous ironstone with green ooliths and shell fragments. .	3	0

By the side of Whitecliff Beck, near Loftus, a deeply weathered, slipping section is exposed.

	ft.	in.
Dogger		
Pebbly siderite-mudstone	1	3
Greenish ironstone	1	4
Siderite-mudstone lenses in sandy ironstone . . .		8
Shelly chamosite-oolite, greenish yellow when weathered .	1	6
Upper Lias		
Shales with rows of chocolate mudstone nodules . . .	7	6

The rock described as greenish ironstone 1 ft. 4 in. shows some very remarkable features in thin section, apparently new to petrography, and will be described in detail in a later section.

AGE OF THE COASTAL DOGGER

Although the massive coastal Dogger is fossiliferous in only one district, at Mulgrave and Sandsend, it may be regarded as being for the most part of upper *opalinum* (Lower Aalenian) age (Macmillan, 1932). In Sandsend Alum Works, however, the upper block of Dogger sandstone, which passes laterally into shales with siderite-mudstone nodules, is separated from the eroded upper surface of the lower block by a pebble bed. This may indicate a marked time interval, although faunal evidence is lacking.

In Loftus Alum Works the Dogger is represented by a thin pebble bed which is overlain by several feet of dark shales with siderite-mudstone nodules yielding *Ludwigia murchisonae* (Black, 1934). These *murchisonae* beds (Upper Aalenian) have been definitely recognized on the coast only at this locality.

although to the south-west beds of closely similar lithology rest upon the massive Dogger. At Sandsend, Whitby Spa Ladder, Howdale, and above Peak Stele rows of small nodules of tough siderite-mudstone, sometimes oolitic, rest in a dark shale on the sideritic Dogger sandstone, and although these have as yet failed to yield fossils they may represent the *murchisonae* beds.

PALAEOGEOGRAPHY AND CONDITIONS OF DEPOSITION

The two most striking features of the coast Dogger are the marked facies difference on each side of Kettleness and the sudden disappearance of the Dogger between Boulby and Loftus Alum Works, north-west of which it only occurs sporadically. These will be dealt with in turn.

Between Kettleness and Hinderwell a number of borings were put down by the Skinningrove Iron and Steel Company to investigate the distribution and iron content of the Dogger (Tonks, 1923). Although the iron content was frequently high, the bed was found to be too variable in thickness to be economically worked. From these borehole records Tonks demonstrated that the Dogger is absent as a massive bed along a N.E.–S.W. belt which passed through the Kettleness Alum Works and about 300 yards south-east of Kettleness Station.

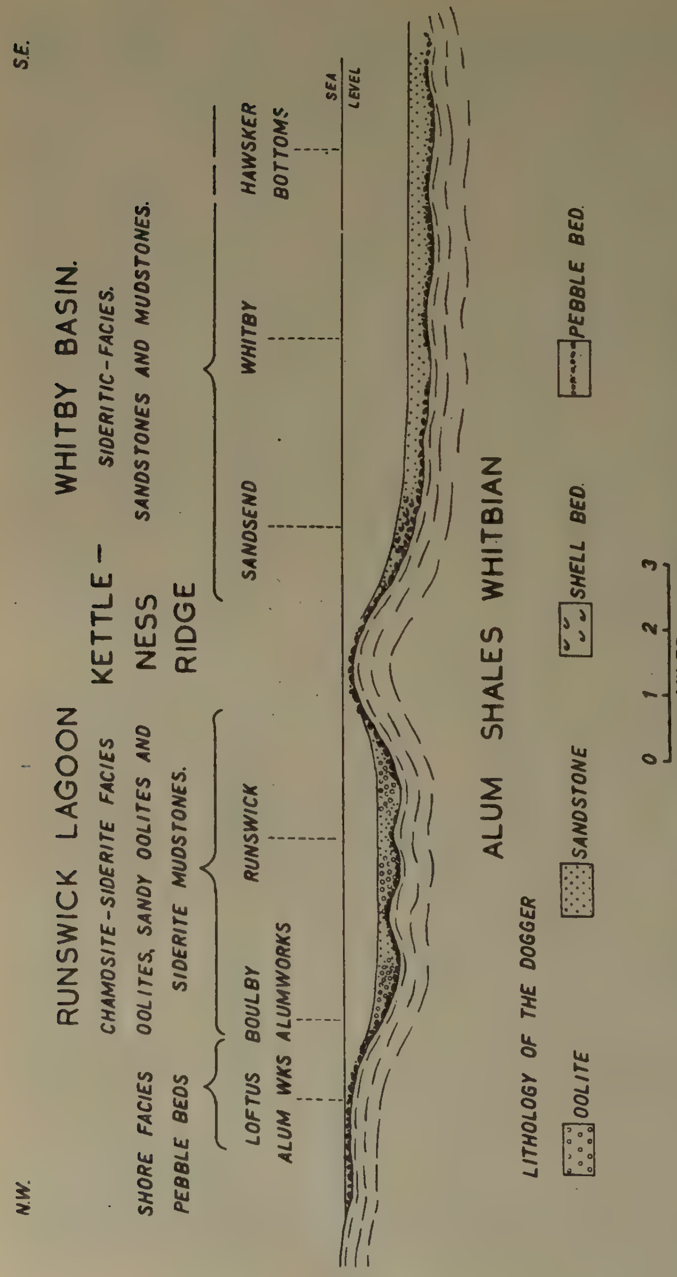
It is significant that the belt along which the Dogger is absent or represented only by a thin pebble bed serves as a barrier to separate two markedly different facies. From Peak to Kettleness, a distance of 12½ miles, the Dogger is represented by a sideritic sandstone with subsidiary developments of shale and siderite-mudstone. To the north-west and west of Kettleness for about six miles it is characterized by sandy chamosite-oolites and chamositic sandstones, culminating in the developments of fine chamosite-oolites at Boulby, Port Mulgrave, and Cat Beck. (For petrological descriptions see later.) In this region siderite-mudstones are still present, but sideritic sandstone plays only an insignificant part.

It should be emphasized that the absence of the Dogger or its development as only a thin pebble bed at Kettleness is not due to its subsequent erosion by an Estuarine washout, as may be seen at the Scar section, near Whitby, or in the Alum Works at Peak or Boulby. The massive washout sandstones, although present capping the cliff at Kettleness, occur only at a higher horizon and, as may be seen from the measured section (p. 189), are separated from the Dogger pebble bed by a few feet of well-bedded Lower Estuarine sandstones or clays through which the washouts have failed to erode. It is also evident that the Dogger thins rapidly approaching this belt, both from the south-east and the north-west, to be finally represented by the pebble bed.

These two features, the marked facies difference on each side of the belt and the thinning of the Dogger towards it from each side suggest that this area, to a limited extent, controlled Dogger sedimentation of the coastal region. During Dogger times it was probably a low submarine ridge or shoal of Whitbian shale capped by chocolate mudstone, sufficiently shallow for no fine sediment to accumulate on its crest, which was about ½ mile wide. Only the coarser pebbles could persist in this environment which may even have been between tide marks, the finer material being winnowed out by wave action and carried into deeper water down the gently inclined flanks. To the south-east a sideritic sandstone accumulated, while the north-west was characterized by chamosite-oolites with a variable amount of sandy detritus and by chamositic sandstones. It is not suggested that this ridge, which may be referred to as the Kettleness Ridge, was in any way a complete barrier between the two areas on each side of it, or that sedimentation on one side was completely independent of the other.

Certain evidence makes it also possible to delimit the north-western boundary of the area within which the sandy chamosite-oolites were laid down. North-west of Boulby Alum Works the Dogger does not occur except in two sporadic outcrops near Brotton and Loftus. No massive beds are present at this horizon, only a thin pebble bed separating the Alum Shales of the Whitbian from the shales and mudstone nodules of the Upper Aalenian above. It is considered that the waters in this region were too shallow for Dogger sediments to be deposited. The thin pebble bed marks the position of a beach on or about sea level which persisted while the Dogger was being deposited over the rest of the coastal region. In only a short distance to the north-west these shallows gave place to the low lying, densely vegetated land surface, but were broken by small indentations such as the Brotton-Loftus inlet, which was connected with the chamosite-oolite lagoon and was sufficiently deep for similar sediments to accumulate.

It is not unlikely that the two principal areas of deposition, the inner Runswick Lagoon in which chamosite-rich rocks were laid down, and the Whitby Basin, seaward of the Kettleness Ridge, where the sideritic sandstones accumulated, were them-



TEXT-FIG. 4.—Conditions of deposition of the Dogger of the coastal region.

selves subdivided into subsidiary basins, in each of which developed rather specialized conditions. From the detailed descriptions given above (p. 183) it would appear that a ridge similar to that at Kettleness existed to the south-east at Stoupe Brow, although the evidence is less conclusive. It is apparent that the massive Dogger thins from both directions towards a point midway between Stoupe Brow and Peak Alum Quarries, in each case being replaced by a pebble bed. Unfortunately the critical contacts are not exposed and borehole evidence is entirely lacking. A facies difference does exist on each side of this ridge though less well marked than at Kettleness, so that in Peak Alum Quarry the Dogger may be more correctly described as a sandy siderite rock, in slight but definite contrast with the sideritic sandstone in the Howdale district. Although the direction of this axis cannot be determined, the unusual topography of Stoupe Brow and Howdale suggest that N.E.–S.W. is most likely. Similar minor axes may explain the distribution of the purer oolites within the lagoon north-west of Kettleness, lying in quieter pockets and separated from each other by more sandy chamositic rocks which are sometimes current bedded. Unfortunately exposures are not sufficiently continuous to prove this.

It is therefore concluded that the originally uniform Liassic basin of deposition was subdivided, by early Aalenian times, into a land area to the north-west, pebbly coastal shallows not unlike Morecambe Bay at the present day and a lagoon separated from a slightly deeper basin by an off-shore shoal, each of which areas can be accurately delimited (Text-fig. 4). From the almost invariable occurrence of the Yeovilian-Whitbian chocolate mudstone immediately below the Dogger, both in the areas of deposition and in the shallower belts, it is concluded that this profound physiographical change was of tectonic origin. From evidence in adjacent regions it appears that at the end of Yeovilian times North-East Yorkshire was gently folded, the crests of the anticlines rising up to or above sea-level, dividing the region into separate areas of deposition in which different lithological types accumulated.

The *murchisonae* beds of Loftus Alum Works and their possible south-eastern equivalents represent the final marine phase before the incursion of the deltaic Estuarine Series. They were laid down in waters very slightly deeper than had prevailed during Lower Aalenian times, which flooded over the shallow coastal flats to a sufficient depth to allow these shallow water sediments to accumulate.

(*To be continued*)

The Mapping of Head Deposits [1]

By H. G. Dines, S. E. Hollingworth, Wilfrid Edwards, S. Buchan, and F. B. A. Welch

Introduction

WIDESPREAD over England and Wales there are superficial deposits of a structureless and rubbly character that can be classed neither with true glacial deposits nor with river drifts. These are especially noticeable beyond the southern limit of glaciation, but they also occur, with less frequency, within the glaciated regions. Geologists in the early part of the last century, unhampered by pre-conceived ideas, frequently described such deposits, and in 1839 De la Beche, probably adopting a quarryman's term for overburden, gave certain occurrences the name Head. In later years Pleistocene classification, embracing both glacial and river drifts, took little or no account of these apparently irregular accumulations. Only those cases that presented special characters or were extensive and thick were shown, under a variety of names, upon geological maps.

During the past few years the present authors, amongst others, have paid a considerable amount of attention to the mapping of these deposits, and now propose to group them under the general term Head.

From the published accounts of observers in arctic regions and elsewhere it is clear that the deposits in question are usually the result of the phenomenon known as solifluxion. This term, which signifies soil-flow, is perhaps not too happily chosen, for the word " soil ", taken even in its broadest sense, implies only the top foot or two of the earth's crust, while it is evident that not only may the agencies that produce solifluxion extend to much greater depths, but also the resulting deposits may be many times that thickness. Nevertheless, the term solifluxion is well established and of world-wide acceptance, and the deposits under discussion, which in places may reach a thickness of 50 ft., definitely belong to the class covered by the term. There can be no doubt that solifluxion is a link between rock weathering on the one hand and river deposition on the other.

Head has now been mapped in a number of districts in England. It has its own peculiar mode of origin and formation, and the mapping of it has, therefore, proved as rational as that of the glacial or river drifts. In the following pages the authors attempt to indicate the type of deposit which it is proposed to class under the term Head and to explain the characteristics of this type of drift and its mode of occurrence, illustrations being given by examples from various districts.

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[1] Published by permission of the Director of the Geological Survey.

HISTORICAL

The following historical account shows the growth of ideas in England regarding the origin of Head and diversity of terms that have been used to describe these deposits.

One of the earliest accounts is that by Borlase in 1758 describing a deposit overlying Raised Beach at St. Just, Cornwall. He states (p. 76), " In a creek, called Por'nanvon, in the parish of St. Just, Penwith, near Cape Cornwall, in the Northern part of the cliff, inserted under the clay and rubble [Head], are ranged horizontally many rowes of large and small roundish pebbles of the granite kind [Raised Beach] : the covering of this *stratum* is fifty feet deep . . . on the North end, but only twenty . . . on the South, consisting of a rough yellow clay, charged here and there with large and small stones, all with their angles on. . . . In short, the sand of these interstices [between pebbles of raised beach] though now fifteen feet higher at a medium than full-sea mark, had all the evidence which could be expected, that it had come from the sea, and was afterwards covered by a load of rubbish, from twenty to fifty feet deep."

Borlase thus recognized the Raised Beach as such and noted the essentially angular nature of the Head.

In 1778, Pryce in his account of prospecting for minerals by " shoding " gives an accurate description of the detrital and transported character of a similar deposit inland. He states (p. 124), " Another and very ancient method of discovering Tin Lodes is by what we call Shoding ; that is tracing them home by loose stones, fragments, or Shodes (from the Teutonic Shutter to pour forth) which have been separated, and carried off, perhaps, to a considerable distance from the vein.

" The deluge, they [tin miners] suppose, moved most of the loose earthy coat of the globe ; and in many places, washed it from the upper, towards the lower grounds, with such a force, that most of the backs of Lodes or Veins which protruded themselves above the fast, were hurried downwards with the common mass."

The first scientific description of this type of drift was given by Mantell (1822, p. 274). He classified drift into Diluvium and Alluvium. The former term is restricted to superficial gravel beds produced by the Flood, i.e. by causes no longer in action. The deposits include irregular accumulations of clay, sand, and gravel intermixed with broken chalk flints, indiscriminately distributed over the surface of the land and obscuring the rock outcrops. Such deposits occur on the summit of the Downs, and on the slopes of hills, and valleys.

With alluvium he included local accumulations formed by torrents, bursting of alpine lakes, and causes operating daily. This idea of separating Head deposits from those forming at the present day in this country became fairly general. Most writers regarded the enormous amount of detritus constituting the Head as something totally distinct from anything that could be produced in this country by processes of the present day.

With the Diluvium Mantell (1833, p. 277) groups the Calcareous Bed or Coombe Rock (as it was termed locally), of Brighton. He called the Coombe Rock the "Elephant Bed" (p. 32) from its included mammalian remains.

The first to use the term Head was de la Beche in 1839. He writes (p. 432), "A head of angular fragments is common to all the raised beaches of the coast of the district [Cornwall and Devon], when hills of hard rock rise behind them, showing not only that a considerable decomposition of such rocks has taken place since the beaches were elevated above the present level of the sea, but also that there has been a great movement of the decomposed surface of the hills downwards, covering up all inequalities that presented themselves and rendering the surface more smooth than would otherwise happen. . . . The raised beaches have been covered like other inequalities because they have only remained where the action of the sea was unable to remove the rocks on which they are based. Such situations would be favourable to the accumulation of head, inasmuch as the fragments which previously fell from the cliff . . . would now fall and accumulate on the raised beach, mingled with the portions of rock which by the action of rains were washed down the slope of the adjacent higher grounds. . . ." De la Beche thus emphasizes the angular nature of the deposit and explains its accumulation by rainwash and talus.

Godwin-Austen (1842) writing on South-East Devon observes the extension of Head inland. He notes that these deposits of local debris are not confined to the valleys, but invest the slopes and crown the summits of many minor ridges. He recognizes that they are not the product of some sudden torrential period, for he states, "In thus classifying together the accumulations on the high grounds with those in the bottoms of valleys, it is not implied that they are exactly of the same geological age, or referable to some peculiar period of dispersion, but that they are the results of those agents, which, for a long period, must have been in operation over this district." Similar views were expressed in 1867 by Pengelly.

In 1851, Godwin-Austen groups the Head under the name of Sub-aerial Beds and regards Mantell's Elephant Bed as of similar age and origin. He states (p. 121), "The accumulation of materials . . . [Subaerial Beds] occurs in a vast number of sections to be observed along the coasts of Devon and Cornwall . . . [it] has only been incidently noticed, and generally under the vague term of 'head'."

He is in accord with De la Beche in stating (p. 122) that the materials are always strictly local as to origin, and the fragments sharp and angular.

He then sets out a view, widely held, that the angular head was formed under conditions totally distinct from those obtaining at the present, stating (p. 123). "The upper surface of these masses of detritus are now necessarily receiving annually the accession of materials, from the joint operation of decomposition, and the transference of the products to lower levels: . . . but the nature and scale of operations now in progress are limited to conveyance of material in the minutest state of subdivision, and imply only the conditions of slow atmospheric decomposition: no accession of fragmentary beds takes place now . . . nor has been made for some long time past. . . . We everywhere may observe a passage downwards into beds which mark a time when the degradation of the surface proceeded much more rapidly than by the mere effects of decomposition, and when fragments of rock, and even blocks of large dimensions in certain localities, far exceeding the moving power of any rainfall, were conveyed down the very slopes along which the minutest particles of matter only are now carried."

Regarding the origin of the angular fragments in these Subaerial Beds he makes the important statement (pp. 129, 130), ". . . it seems absolutely necessary to call in the operation of cold to adequately account for them." To obtain such conditions he postulates "an elevation of great amount, such as would place the whole of the higher portions of this country in regions of excessive cold". This appears to be the first mention of cold conditions for the production of Head.

In the same year Murchison (1851) wrote his paper on the Flint Drift of the south-east of England. This drift he termed

Angular Flint Drift or Angular Drift. He recognized that flint, chert, and fragments derived from Tertiary formations take part in its formation. The Brighton Breccia or Coombe Rock (Elephant Bed) he regarded as nothing more than a sharply-fractured variety of the general drift covering south-eastern England. In a section (fig. 3, p. 353) he clearly showed this drift capping a hill and spreading down the dip-slope, whilst the scarp face separates the hill-top accumulation from similar material at the base. Murchison attributed the drift to strong currents produced by violent oscillations of land and by earthquakes. The term Head is not mentioned.

Prestwich, also in 1851, described the drift at Sangatte Cliff, Calais, which he compares with Coombe Rock, of Brighton. He held the same views as Murchison on its origin.

Meanwhile Joshua Trimmer stated (1851, p. 32), that the majority of soils and subsoils in the British Isles are composed in part of the debris of the rocks on which they rest, and in part of materials transported from various distances by forces of considerable intensity, differing from ordinary atmospheric action, which were in operation at the close of the glacial period. Later (p. 34), he attempted to show that the "soils" covering the Chalk in Kent are analogous to the "erratic warp" of Norfolk, i.e. that they are the result of aqueous transport, and not due to atmospheric weathering. The deposit he figured appears to be clay-with-flints mixed with varying amounts of Eocene material. The name Clay-with-Flints was given by Whitaker to such material in 1861 (p. 54), though it was not until 1864 (p. 64) that he suggested an explanation of its origin, viz. "the Clay-with-Flints is of many ages, and may be forming even at the present day, . . . owing in great part to the slow decomposition of the chalk under ordinary atmospheric action." He adds that to the ubiquitous Clay-with-Flints would be added, locally, clays and loams washed from the Tertiary lands.

Codrington (1865) accepted this view, but considered that an overlying deposit of clay or loam was essential to the formation of Clay-with-Flints.

Fisher (1866) dealing with Trimmer's "Warp", regards it as being the "soil" produced from "Trail". The subject was thoroughly treated by Spurrell (1886) and the following terms explained: Warp is used to refer to rain-warp or older rainwash (and not to silty muds formed by settlement from troubled waters). Rain-warp is fine material separated from Trail, leaving coarser material as surface gravel. Trail is material filling troughs and hollows. It is dissociated wholly from the beds whence it was derived, being the rearrangement of detached and comminuted rocks after thawing of ice. The furrows are due, according to Fisher, to a period of extensive denudation prior to the submerged forest period. "Underplight" is the term used for rocks and beds forming the folds and sides of hollows, which though crumpled are still united to parent rock. The Underplight is the result of movement of ice or thawing soil over the land.

Spurrell supposes (p. 31), "That the folds or Underplight, with the puddled sludge or Trail, may have resulted from the heavy pressure of a superincumbent mass of snow on a soil in a condition capable of yielding, and frequently repeated." He quotes reports of various arctic travellers and explorers in support of this; Nares, Kane, Nordenskiold, etc.

Again, the Underplight may have resulted from "intermittent flowing, by its own weight, of a soil undergoing a thaw, that is, in a viscous state", or sludging from higher to lower ground. Examples are quoted from Sir E. Belcher's *Arctic Voyage*.

Ussher employs the term Head in the same sense as previous writers. He regards (1878, p. 456) the Clay-with-Flints and Cherts of the West of England as a much earlier formation than Head, and as ". . . the relics of an ice-bed metamorphosed *in situ* . . ." of the first Glacial Period. The period of formation of Head he regards as indicating the effects of the last throes of the Glacial Epoch. The climate had more marked seasons, sharper frosts, and heavier rainfall.

In his post-Tertiary Geology of Cornwall (1879), he regards Head as a deposit carried down from neighbouring higher lands by torrential water or melting snow during a period of great sub-aerial waste and vigorous climate.

The idea that the formation of Head took place under conditions of snow was gradually growing, and this was aided by the observations of arctic explorers and others who had seen snow-sludging in process.

S. V. Wood, Jun. (1882, p. 718), ascribed the angular drift of the non-glaciated areas of England to sludging from higher to lower ground, the angular fragments of rock being the result of frosts. He regarded the Clay-with-Flints as also due to this cause.

Likewise Godwin-Austen considered certain gravels at Guildford to be of glacial origin and, discussing their mode of formation, stated (1884, p. 612), "it is not necessary to suppose anything of the nature of a glacier as we know them in Alpine regions; but what would result, if the cold were great enough, would be the formation of frozen snow-beds on the higher grounds lasting through the heats of summer, and such would be the exact counterparts of those patches of ice, many square acres in extent, that are to be seen at the present day on the wide level plateaux of the Chang Chingmo in Thibet. . . ."

Clement Reid (1887) explained the Coombe Rock as a deposit formed by rainfall running off the permanently frozen Chalk land and forming torrents which would tear up rubble loosened by frost. Thus flat lands at lower levels would become covered by sub-aerial deltas the materials of which would become finer grained the further they were carried.

Prestwich (1892) presented an exhaustive review of the subject, in which older works are summarized. He regarded Head as a variation of a widespread deposit which he termed "Rubble Drift", though the terms were used synonymously in his paper. With "Head" he grouped the oolitic gravel on the scarp edge of the Cotteswolds. He agreed with early writers on the essentially local and angular character of the deposit, and under Head or Rubble Drift he grouped the following types of accumulation:—

(1) Masses of angular detritus and rubble forming Head on raised beaches.

(2) Beds of angular gravel and loam lying on hill-slopes, or projecting into the plains at their bases, and not referable either to marine, fluviatile, or glacial action.

(3) Trails of gravel, not referable to river action, in subsidiary valleys ending at their junction with the main valley in a fan-shaped spread.

(4) Basement gravels of most valleys.

(5) Trails, in some valleys, consisting of blocks of local origin.

(6) Slight, irregular scatterings of angular debris, clay, and loam, or brickearth on the sides and at the bases of hills. Prestwich attributed the formation of Head to an imagined subsidence of 1,000 ft. below sea-level followed by a rapid emergence proceeding spasmodically, each jerk causing divergent currents from the summits of the drowned hills.

In 1894 James Geikie reviewed the whole subject in *The Great Ice Age* (Ch. 27). He considered that the Head and Rubble Drifts are the result of snow-sludging, and stated that such deposits are an extra-marginal facies of glacial drift, formed at the time of maximum glaciation.

In 1906 Andersson having observed snow-sludging and associated processes on Bear Island in the Arctic, introduced the term Solifluxion. He states (pp. 95–6), " This process, the slow flowing from higher to lower ground of masses of waste saturated with water (this may come from snow-melting or rain), I propose to name solifluction (derived from *solum*, ' soil,' and *fluere*, ' to flow ')."

In the same year Reid and Scrivenor (1906, p. 67), compare the Head of the Newquay district with the " stone rivers " of the Falklands and Tierra del Fuego. These stone rivers Andersson (1906, p. 103) regards as a " fossil " occurrence of solifluxion. Reid and Flett (1907, pp. 77–8), considered Head to have been distributed by floods of snow-melt water of the glacial period, i.e. as fluvio-glacial.

There has been little recognition in Britain of the importance of the processes of solifluxion as is shown by Hollingworth (1934, p. 168), though a glacial origin for certain types of Clay-with-Flints on the Chiltern Hills was put forward by Sherlock and Noble (1912) and in 1915 Dewey and Bromehead (p. 81) described, under the heading Landslip and Soil-creep, " material which . . . is difficult to show on the map on account of its indefinite character and obscure limits. Some of it is the result of solifluxion or soil-creep during the cold period that appears to have followed the deposition of the Taplow Terrace. The superficial parts of beds of all ages have moved down slopes to new positions, and even where there is no slope the subsoil to a depth of 2 or 3 yards has been contorted and mixed."

In 1924 Bromehead (*in* Dewey and others, p. 106), gave the name Coombe Deposit to material filling coombes in Chalk country around Dartford, consisting of a varying mixture of local material, such as Chalk rubble, resorted Eocene clays, sands and loams and dirty gravel, with a tumultuous structure. In 1930 Edmunds used the term solifluxion in explaining the mode of formation of the Coombe Rock of Brighton.

Discussing the origin of the Clay-with-Flints of the North Downs, Edmunds (*in* Dines and Edmunds, 1933, p. 151), after dealing with the solution of the Chalk, writes, " The solution factor alone, however, is inadequate to explain the whole of the phenomena exhibited by the Clay-with-Flints of the present area. Beds around Burgh Heath and Walton Heath, for example, vary in lithology almost from yard to yard and the melange of material, consisting of red sand, yellow sand, red clay, purple clay, small flint pebbles, large worn flint cobbles, and unworn flint so characteristic of this deposit, in places overlies Thanet Sand, which shows little or no sign of disturbance, and in such a way that solution of Chalk and consequent subsidence is ruled out. . . . This type of Clay-with-Flints . . . appears to have been assembled under glacial conditions ; the deposit, however, does not resemble those left behind by large ice-fields such as existed north of the Thames, but is more satisfactorily explained as being material disturbed and resorted by a local ice-cap or snow-field."

Fans of contorted gravelly material mixed with chalk rubble were recognized by Jukes-Browne and Osborne White in the Wallingford district, on the Chiltern escarpment (1908, pp. 89–92). These were later regarded by Osborne White as having been formed during periods of thaw in a cold climate (1932, p. 82). Edmunds has noticed the widespread character of such deposits and, in dealing with occurrences in the Saffron Walden district (*in* White, 1932, p. 44), and near Dorking (Dines and Edmunds, 1933, pp. 157, 158), introduced the term Taele Gravels because of their similarity to frozen soil or " tjale ". Edmunds states (p. 157), " They [Taele Gravels] form an intermediate grade between solifluxion deposits, such as much of the Coombe Deposits of the South of England, and true river gravels.. . ."

The above summary emphasizes the necessity of bringing all the members of this type of deposit together into a recognized group.

HEAD DEFINED

On the published Geological Survey maps of England a number of structureless deposits of different composition and irregular distribution have been given such names as " Head " (of Devon), Pebbly Clay and Sand, Talus, Rainwash, Downwash Gravel, Coombe Rock or Coombe Deposits, Taele Gravel, and Angular Chert Drift. An examination of these shows that they have several characters in common and affinities in mode of origin. This also applies to certain deposits hitherto included in Alluvium, Plateau Gravel, High Level Gravel, Pebble Gravel of Doubtful Age, Valley Gravel, Dry Valley Gravel, Brick-earth, and Clay-with-Flints.

These drifts, in common with certain others now being mapped by officers of the Survey, are all of variable composition, are derived from local formations (either solid or drift) and are clearly the result of slow flow, from higher to lower ground, while over-saturated with water from melting snow or ice, rain, or lines of springs or seepages. It is now proposed to class all these together under the general term of " Head ".

Since Head originated essentially from disintegrated solid or drift deposits, it may be angular, subangular, or well-rounded, depending on the nature of the parent. During transport it may have received a certain amount of attrition, but usually the distance over which it has been carried is too short to contribute appreciably to rounding. Because it is not far from the point of origin, it is but little removed in composition from its parent material, although it will naturally have incorporated some of the material over which it passed.

The deposits may be distinguished from those of truly glacial origin by the fact that they are composed entirely of local material, though this, of course, may itself include far-travelled stones. Lack of stratification, grading, and rounding of the fragments (unless derived from pebbly deposits) serves to distinguish them from river deposits, but occasionally a crude stratification may be found.

Head occurs capping high ground, on slopes, or in valley bottoms. In some cases that on high ground is derived from underlying solid rocks and has undergone but little lateral movement, as on the Lower Greensand escarpment around Sevenoaks. In others it occupies isolated plateaux once connected to higher ground from which the material was carried, as at Limpsfield Common, Surrey. Head may form a continuous spread over the top and down the sides of hills to the gently sloping ground below, as on Lewesdon Hill, Dorset. In some instances a steep, drift-free slope separates Head of the high ground from that below.

At the coast Head has been observed overlying raised beaches, as at St. Just, Cornwall, and it occurs also as an accumulation in valley bottoms or spread out as fans where a valley opens into lower ground, as in the neighbourhood of Dorking.

That some Head must have reached river level during the deposition of river terraces is shown by the fact that it has been found with waterworn and stratified river-deposits above and below it. In some cases it clearly provided the material which the stream subsequently rolled and sorted to form its terraced gravels.

As with other deposits, the mapping of Head will naturally depend on the particular character of the ground under survey and to some extent upon the individual surveyor. Thin skins of surface wash, often relegated to " topsoil ", belong in many instances to this class of deposit. These frequently represent extended " feather-edges " of thicker deposits of Head. Where it is possible to differentiate between types of Head it is proposed that the differences, if necessary, be indicated on the maps. Thus, some of the brick-earths along the southern slopes of the Thames estuary consist of Head derived from Tertiary deposits. In such cases the colour and symbol for brickearth would be retained, chiefly on account of the economic value of this type, its mode of formation being discussed in the memoir accompanying the map. Again, the term Pebbly Clay and Sand, previously used for deposits on the Chilterns, will continue to be used in the Dorset area because it aptly describes a certain type of deposit, though in Dorset it is classed as Head. Coombe Rock is a peculiar type of Head for which it would be advantageous to retain a special name and colour, but its counterpart, Coombe Deposit, has no distinctive features to separate it from other Head deposits. In the case of Clay-with-Flints, the colour and symbol at present in use may be retained except where the material is proved to have been transported with or without the incorporation of Tertiary or other material ; in that case it falls within the category of Head. The same applies to other drifts hitherto classed amongst those of fluviatile origin, when they can be shown to be unbedded accumulations of detritus from existing or pre-existing higher ground. Some examples of the deposits being mapped as Head are given in the next section.

SOME EXAMPLES OF HEAD MAPPING

West Yorkshire.—Head occurs in abundance in valley bottoms and on the lower slopes of hillsides in those parts of West Yorkshire which escaped invasion by ice during the later (York-Escrick) stage of the Newer Drift period (*see* Edwards *in* Hudson, 1938, p. 338).

It varies widely in composition according to the nature of the rocks (solid or drift) which occur on the slopes above. In Millstone Grit and Coal Measures areas it is generally an unbedded mass of loam or clay, crowded with rock fragments such as sandstone, mudstone, and ironstone, and with stones derived from boulder clay. Apart from the latter, the rock fragments are commonly angular to sub-rounded, of various sizes, but mainly below that of boulder grade except where the slopes above contain outcrops of massive sandstone. In this case blocks up to several feet across, angular, or rounded as by sub-aerial weathering, occur in the Head.

Fragments of mudstone and shale in places form the bulk of the deposit. A matrix of more or less pulped mudstone may be present, as well as considerable masses of the same material, which show varying stages of disintegration. In drift-covered areas the Head may consist of rearranged boulder clay, and is in many instances impossible to distinguish from that material except by its peculiar topographic features.

In various localities, but especially in the central and eastern parts of the Yorkshire Coalfield, wind-faceted cobbles, mainly formed from stones derived from the Older Drifts, are common in the Head (*see* Edwards, 1936, p. 17).

The deposits on the Permian outcrop consist of stony loams, with fragments of Magnesian Limestone and, in certain localities, a high proportion of red marl. Smoothed blocks of sandstone derived from boulder clay are generally present.

In places a rough stream-laying of material of different grades is visible, while in rare cases a rubbly loam is found passing laterally into, or interdigitating with, water-laid sand and clay or true terrace-gravels of streams.

These deposits usually form fairly even-surfaced sheets in valley bottoms. They tend to occur most frequently near the heads of shallow valleys where the thalweg slopes at 2° to 4°. They are not usually in evidence on slopes steeper than this, except where they contain a high proportion of large boulders. In such cases, which are confined to the more hilly Millstone Grit areas, they rest on slopes as steep as 8°.

The valley bottom sheets bear a superficial resemblance to modern alluvium, but may usually be distinguished from it, apart from their lithology, by the following features: the margins of the deposits are seldom well defined; in cross-section the surfaces of the sheets are not flat, but show low, irregular undulations with a tendency to a humping-up in the middle which is pronounced in narrow valleys; usually the Head lies alongside streams which slope too steeply for modern alluvium to form. Where the two occur in juxtaposition the alluvium either overlies the Head or occupies a channel cut into it.

The sequence of glacial stages recognized in West Yorkshire is as follows:—

(1) An early, intense glaciation, with deposition of boulder clay far beyond the southern limits of the area, comparable with the Great Eastern Stage of the Older Drifts. Evidence of more ancient drifts is present, but may be disregarded for the present purpose.

(2) The Main Dales Glaciation (Newer Drifts), affecting a more restricted area. Boulder clay and other deposits were laid

down in two stages, the earlier covering a wider area than the later (*see* Edwards *in* Hudson, 1938, p. 337).

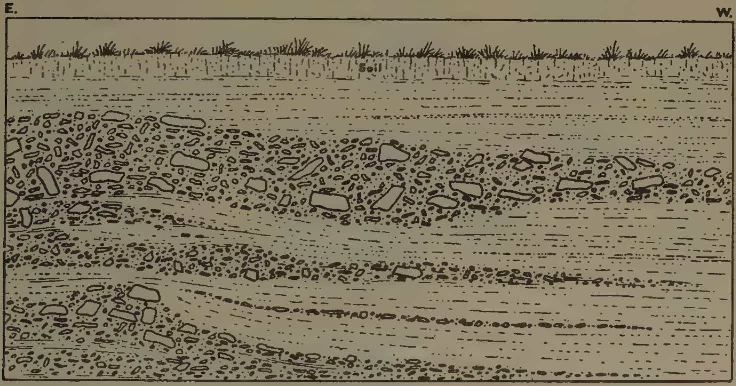
There was considerable dissection during the interval between Older and Newer drifts. All the deposits so far identified as Head lie on the surface produced by this dissection, and are thus later than the Older Drifts. Head is seldom found in the area which was covered by the last ice advance, but is common outside that area. In the main it is thus either contemporaneous with or older than the later stage of the Newer Drifts.

Valley trains contemporaneous with the later stage of the Newer Drifts extend down Wharfedale and Airedale and pass eastwards into river terraces of normal appearance. Sheets of Head passing laterally into these terraces have been observed at five localities in Wharfedale and two in Airedale. Much Head was thus formed in the periglacial zone during the final stage of the Newer Drifts. In Airedale a sheet of Head is graded to a terrace which may correspond to the earlier stage of the Newer Drifts.

The type of Head found on Millstone Grit in the higher parts of the Pennines is well developed on the north and east flanks of Pike Lowe, 4½ miles south of Penistone (*see* Edwards *in* Bromehead and others, 1933, p. 135). On the north it is exposed to a depth of 15 ft., and consists of gravelly clay with many boulders and smaller fragments of the sandstone characteristic of Pike Lowe. It lies near the foot of a long 8° slope which extends from the summit of the hill, and it has been cut to a depth of about 50 ft. by a small stream (Shaw Clough). On the east flank the deposit consists of masses of angular blocks up to several yards across of the Pike Lowe sandstone, piled in irregular mounds which form a conspicuous feature. Here it is perched high up above the deep valley of Ewden Beck, and appears to have been partially destroyed by the headward development of the valleys tributary to this beck. In both cases the dissection, which is active at the present day, probably began post-glacially.

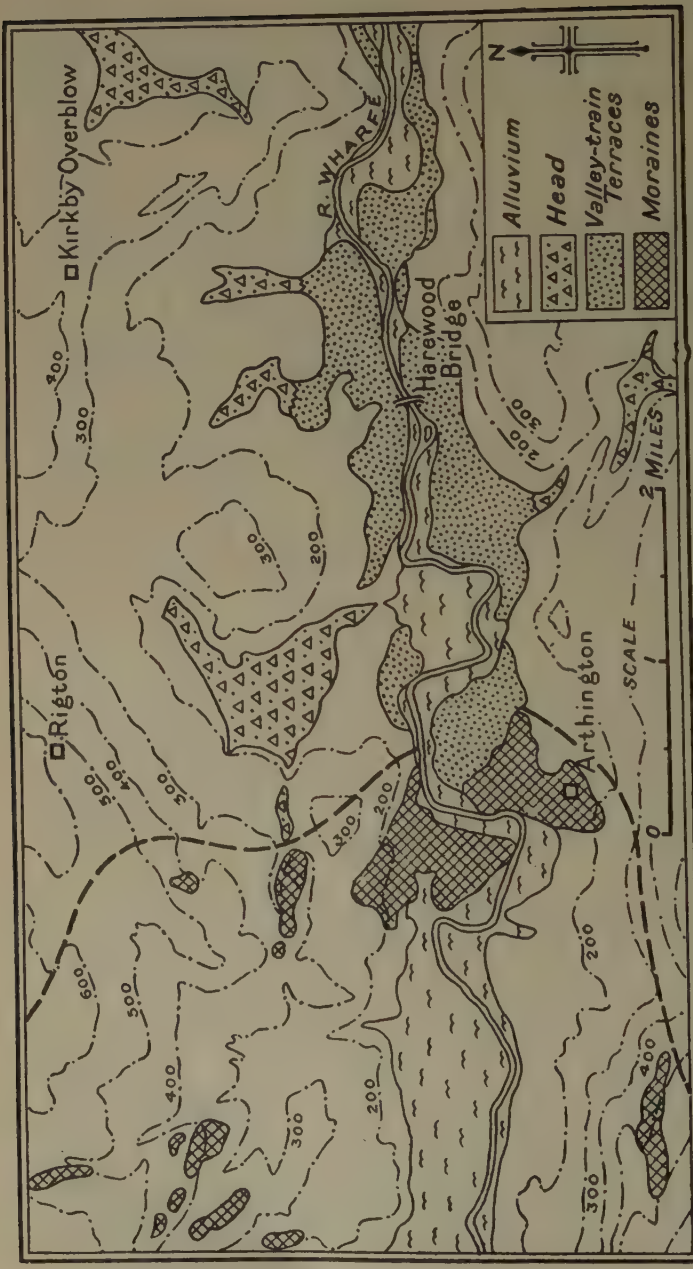
A deposit which, although not referred to as Head, appears to have the characters of this deposit, was cut in making a reservoir dam in the Booth Dean Valley, near Rishworth (*see figure by* A. G. Beaumont *in* Wray and others, 1930, fig. 12, p. 135). The material is a compact clayey gravel charged with pebbles, rounded blocks, and angular fragments of Millstone Grit sandstone. It fills an old valley extending about 35 ft below present stream level: it thins out on the south agains the valley side, but extends up the north side of the valley fo an unknown distance as a layer about 15 ft. thick. No boulder clay has been observed in this part of the Pennines.

In Airedale glacial gravels, sands, and silts are interbedded with layers of stony loam; a section can be seen in a gravel pit 700 yds. south-east of Newlay Bridge (Text-fig. 1). The stony layers are packed with angular fragments of ganister and sandstone up to a foot in length, and are obviously derived from a Coal Measures sandstone which crops out on the hillside 300 yds. to the south, the slope between being about 5°. Some of the ganister fragments show polishing which may be attributed to erosion by wind-driven sand. The section illustrates the interdigitation of Head with gravels which are probably of late glacial date.



Text-fig. 1.—Section of Head in Newlay Gravel Pit: height about 10 ft.

Near Harewood Bridge, in Wharfedale, 5 miles south of Harrogate, the morainic drift of the later (York-Escrick) stage of the Newer Drifts extends to a large terminal moraine at Arthington. Valley-train terraces stretch down the dale from this moraine, and northward of Harewood Bridge appear to pass laterally into two patches of Head which occupy shallow tributary valleys (Text-fig. 2). No junction of the two deposits is visible, but there is little doubt that they are contemporaneous because they pass into each other with no suggestion of a change in slope. The Head is composed largely of rearranged boulder clay, which covers part of the valley and is referred to the earlier stage of the Newer Drifts. Both the Head and part of the terrace are overlain by a stoneless clay resembling brick-earth. Other



TEXT-FIG. 2.—Sketch Map showing the relations of the Head to the Valley Train Terraces of the Newer Drifts in Lower Wharfedale. The broken line indicates the approximate eastward limit of the moraines of the final (York-Escrick) stage of the Newer Drifts. Unlabelled areas are Millstone Grit largely covered by Boulder Clay.

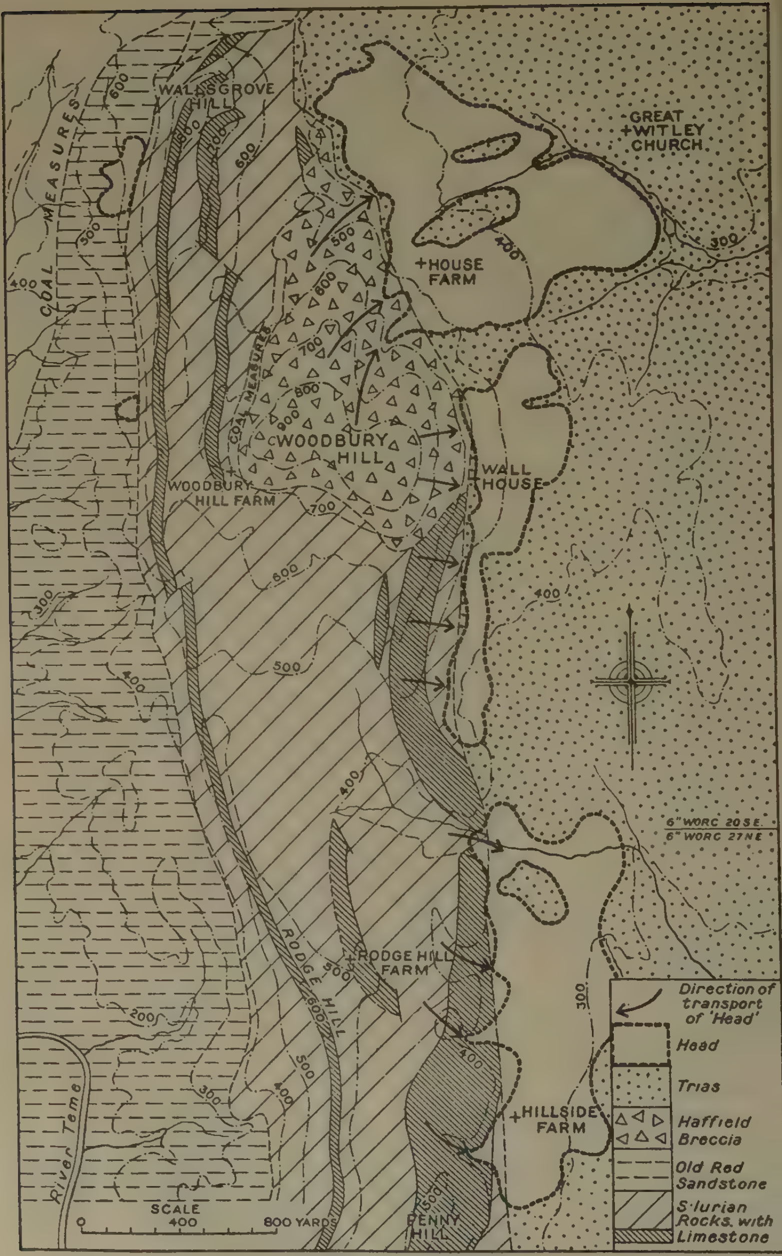
patches of similar Head occur outside the limits of the morainic drifts, but within those limits none has been detected.

West Midlands.—Outside the usually accepted limits of the Newer Drift in the West Midlands, sheet-like accumulations of local debris are known both within and beyond the conjectured limits of the Older Ice sheets. They have in some cases been recognized as products of solifluxion processes during cold climate (Hollingworth, 1936, p. 63; Wills, 1938, p. 186). An instructive example occurs east of the Abberley Hills in West Worcestershire where sheets of debris derived from the Silurian and Carboniferous rocks of this range are found on the lower ground of down-faulted Triassic rocks. A contoured geological map of the area between Great Witley and Martley is shown in Text-fig. 3. The three patches serve to illustrate general points such as variations in composition and in relations to topography. The northernmost or House Farm occurrence consists of coalescing sheets of angular to subangular rock fragments derived from steep-sided valleys in the Woodbury Hill mass of the Haffield Breccia. This sheet also illustrates the tendency for Head to occupy gentle depressions in the Triassic lowland with bare Trias rising through to form slightly higher ground, thus giving at first sight an appearance of outliers of Trias lying on "solid" older rocks.

The second, or Wall House, patch has been derived almost entirely from the hill slopes to the west by direct sloughing off of rock waste. Its northern half is thus composed of breccia debris from the southern part of Woodbury Hill, whereas its southern part is composed of Wenlock Limestone debris in a clay matrix.

The southernmost or Hillside Farm occurrence differs somewhat from those to the north in that the Wenlock Limestone ridge to the west is not so high or continuous, being broken by four gaps occupied by small streams which head into the strike depression of Ludlow Shales farther west. The drift, which is up to 10 ft. thick, tends to be thickest and broadest opposite these gaps and contains a large clay or shale fraction. It seems to have been formed in part of material transported through the gaps.

The great spread of drift to the north-east and east of Woodbury Hill is in contrast with the absence of such deposits on the western and southern sides. This suggests that the direction of the slope is, through the varying influence of the incidence of the sun's heat, a controlling factor with distribution of the Head and invites comparison with the formation of corries and



TEXT-FIG. 3.—Sketch map of Head deposits near Woodbury Hill, Abberley Hills, Worcestershire.

nivation processes. The absence of any Head derived from the steep western slope of the hill range is, in general, confirmatory of this interpretation but here another factor may be present.

There is a striking contrast between the maturity of the surface of the Trias immediately east of this part of the Abberley Hills and the youthful deeply dissected topography of the Old Red Sandstone marls west of the range (*see* Text-fig. 3). This is due to the fact that whereas the Pleistocene rejuvenation of the Severn tributaries in the east has not reached the region shown in the map, the pronounced rejuvenation of the main valley of the Teme lying within a mile to the west of the range has resulted in active deepening of tributary valleys. This would undoubtedly favour the removal of Head products.

The spreading out of the debris implies a change from the conditions which produced the mature surface of Triassic rocks on which the Head rests. Its universal cover of vegetation indicates that accumulation is not active under present conditions. Its position in the glacial sequence in the Severn drainage area is at present in doubt. Possible correlatives are the sheets of Malvernian gravels and Oolite gravels (Gray, 1919), tentatively related in part to the Main Terrace and the Older Kidderminster Terrace of the Severn by Wills (1938, pp. 186, 209–212).

South-West England.—Over parts of West Dorset, South Somerset, and West Devon, Head forms the dominant and characteristic drift. The eastern part of the area, between Dorchester and Blackmoor Vale, comprises typical Chalk downland with dry valleys. The Chalk overlies the Upper Greensand and Gault which in turn rest on Jurassic rocks. To the west the high ground is formed by small patches of Chalk, but chiefly by Upper Greensand in the top part of which there is developed a series of Chert Beds up to 40 ft. thick in places. This chert-capped Greensand gives rise to the highly-dissected plateaux that reach from the Blackdown Hills, south of Taunton, to the English Channel.

The hard material forming the angular detritus of the Head is thus largely made up of flints from the Chalk and chert from the Greensand (*see* Welch and Buchan, 1933, p. 41 ; Welch, 1935, p. 46 ; Welch and Robbie, 1936, p. 59). The matrix depends upon the material incorporated in the sludge during flow from higher to lower ground ; thus in the east of the area Greensand and Middle and Upper Lias sands, whilst in the west Greensand and Trias marl constitute the greater part of the matrix. The term " Head " was used for this material by Welch (1937, p. 44). Head not only occupies the lower ground, but occurs extensively on the high tablelands and ridges where it is frequently associated with Clay-with-Flints. On the old geological map of the district the whole of this upland drift was regarded as Clay-with-Flints, but recently it has been found possible to divide it into (1) true untransported Clay-with-Flints, and (2) Pebbly Clay and Sand.

In the Chalk areas the Clay-with-Flints consists of dark, red-brown tenacious clay containing shattered, unweathered Chalk flints, and reaching an average thickness of 6 ft. Locally, outliers of supposed Eocene sand and gravel are preserved, and in one case these have been proved to overlie the Clay-with-Flints. It is clear, therefore, that here the Clay-with-Flints is due to decomposition of the Chalk and is not a Head deposit.

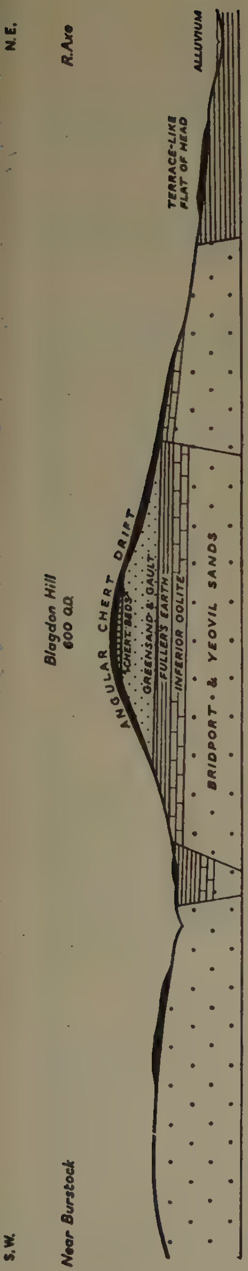
The deposit now mapped as Pebbly Clay and Sand consists of an irregular and in some places incomplete mixture of the Clay-with-Flints and the sands and gravels, so that the resulting deposit is a sandy clay with many flints and rolled pebbles of vein-quartz, schorlrock, quartzite, and chert.

On the Blackdown Hills also similar patches of supposed Eocene materials are preserved, but here the underlying rock is largely chert so that the Pebbly Clay and Sand contains much chert but little flint.

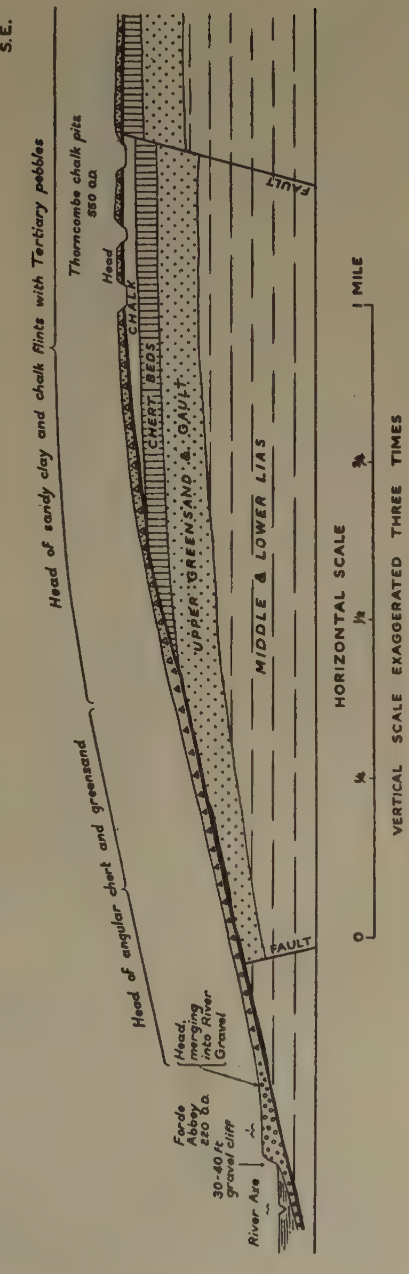
Though the origin of Clay-with-Flints is in most cases obscure, the Pebbly Clay and Sand appears to be due to mixing of pre-existing deposits by sludging, and accordingly such a deposit is regarded as a type of Head.

In steeply dissected country or on scarp edges, the Head capping the high ground is nearly always separated from that on the lower ground by a steep cliff in which solid rock crops out. That immediately below the scarp is clearly of later age than that on the top, for at the time of formation of the latter (presumably during or near the Glacial period) the scarps had not receded to their present positions. We can thus group the accumulations of Head according to their relative ages, but in the case of dip-slopes and areas of gentle relief the Head on the upper ground merges down into that below and separation cannot be effected.

In its passage from higher to lower ground the character of the deposit varies in composition according to the formation over which it has passed. Thus in descending the Culm Valley the Head is first a mixture of Greensand and chert fragments which gradually changes to a reddish loam with chert, and finally, as the deposit spreads farther over the Triassic marl outcrop, to red clay and chert. The thickness of the Head varies



TEXT-FIG. 4.—Section showing mode of occurrence of Head in the Bridport area. Length of section, about three miles.



TEXT-FIG. 5.—Types and distribution of Head on the slopes of the Axe Valley.

greatly ; 6–8 ft. is an average though 14 ft. is often seen beneath the scarps.

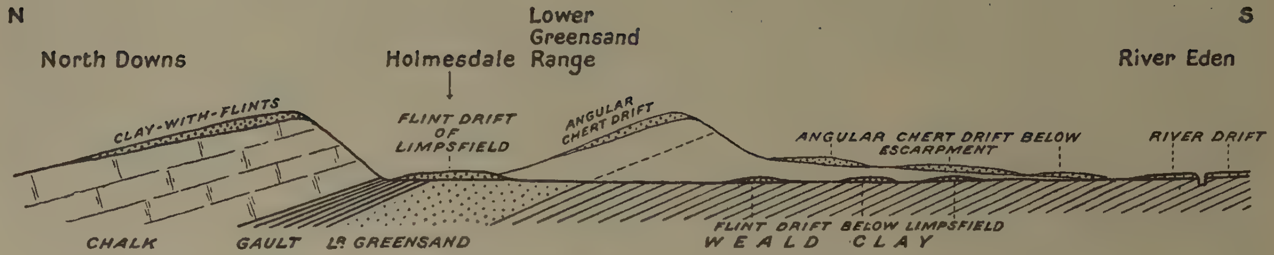
Finally in valley bottoms the material is frequently taken up by rivers and redeposited as river gravels. The point at which the Head ceases and changes into a river gravel is very indefinite and there are no sections to reveal whether there is a gradual passage, or an interdigitation of the two types.

The two following examples taken in the Axe Valley, 4½ miles apart, may serve to illustrate the occurrence and composition of Head as it appears in the area :—

The first section (Text-fig. 4), drawn through Blagdon Hill, shows the simplest case in which the Greensand Chert-capping has supplied the angular fragments which, mixed mainly with Greensand, forms a spread down the slope to 400 ft. O.D. On lower ground Bridport Sand (Upper Lias) is incorporated. Originally the Head appears to have formed a more or less continuous spread down to the present 400-ft. contour, and later it has been dissected by streams. In the present case, just above the river, low flats are developed, identical in topography with river terraces, but composed of unworn angular detritus.

In the second case (Text-fig. 5), farther downstream, the Head shows a more complex mixture. Here, a small Chalk area is capped by " Pebbly Clay and Sand " which has moved down the slope and after passing over the outcrop of the Chert Beds has taken up so much of the Chert that it merges into an angular chert drift. Farther down the slope Greensand and sandy Lias enter into the composition of the matrix. Close to the River Axe the Head passes into true river gravels, which form a terrace, 30 to 40 ft. thick, above the present alluvium. It is from similar gravels farther downstream at Broom Pits that the well-known St. Acheul chert implements have been obtained. There are no exposures showing the actual passage of Head into river gravel.

South-East England.—Several examples of Head may be found in the tract of country that includes the North Downs and the Lower Greensand ridge extending east and west from Sevenoaks (*see* Text-fig. 6). The oldest Head in this neighbourhood is that which overlies the Chalk and is included with the Clay-with-Flints. It consists of a heterogeneous deposit including debris from the Chalk and the Eocene and Pliocene beds as well as from the Lower Greensand. From its position on the escarpment edge it sweeps down the dip-slope, resting mainly on Chalk, but in places overriding patches of undisturbed



TEXT-FIG. 6.—Diagrammatic section across the north margin of the Weald, through Limpsfield gap, showing the relation of the various Head deposits.

Thanet Sand and Pliocene beds and disturbed Blackheath Beds, and reaches its downward limit at about the 500-ft. contour. In exposures it is seen to consist of contorted masses of clay or loam with angular flints and of pebbly portions. Soil indications vary from place to place, the matrix ranging from a light sandy loam through red-brown loam to red, almost plastic clay. The stones in addition to angular flints may consist of black Eocene pebbles, buff battered cobbles presumably of Pliocene age, fragments of ironstone that carries the suite of heavy minerals regarded as peculiar to the Pliocene deposits of the area, and fragments of chert from the Lower Greensand. In addition there are subangular flints with a deep brown patina that may have been derived from old drift deposits now completely obliterated.

Similar to this deposit in its mode of formation and occurrence is the angular chert drift on the Lower Greensand range (*see* Leighton, 1895, pp. 108, 109 ; Dines, 1933, p. 38, 1936, p. 42 ; Dines and Edmunds, 1933, pp. 166, 167 ; Dines, Buchan, and Holmes, 1937, p. 42). In composition this consists of a structureless mass of angular chert fragments set in a matrix of loamy or clayey sand, often bright red in colour, due, probably, to the oxidation of glauconite derived from the Sandgate Beds. From the escarpment edge, where it rests on the upper part of the Hythe Beds, it sweeps down the dip-slope and overlaps the Sandgate Beds. Like the Clay-with-Flints it extends down to about 450 ft. O.D., and is dissected by the dry-valleys and coombes of the dip-slope. It is, therefore, definitely one of the older Heads of the area and has contributed to a large extent to the later spreads on the Weald clay, discussed below. In the neighbourhood of Offham, the extensive spreads of Mereworth Woods extend down below the 300-ft. contour and here the deposit contains scattered ochreous flints, and has presumably incorporated a pre-existing drift of flint gravel on the south slopes of the Vale of Holmesdale. This lower part may, therefore, be later in date than that nearer the escarpment though it is not possible to draw any line of demarcation.

In Holmesdale, on Limpsfield Common, there is on the watershed of the rivers Medway and Darent a spread of Head composed of flints and flint pebbles. The source of these is clearly the Clay-with-Flints and disturbed Blackheath Beds that cap the adjacent Chalk escarpment to the north, though the flints at Limpsfield appear to have become, to some extent, subangular during the process of transport. Although mainly a structureless mass, the Limpsfield Head is locally crudely bedded, and some of the larger oval pebbles are orientated with their flat sides inclined to the north. At its northern end, where the deposit overlies Gault, it has a stiff clay matrix and contains irregularly shaped rafts of clay. Midway the deposit rests on Folkestone Beds, but the clay matrix persists some distance farther south than the base of the Gault before it takes on a sandy character. Similarly the Folkestone Beds are reflected in the matrix beyond their junction with the Sandgate Beds which underlie the southern margin of the Head. It is evident, therefore, that the Head incorporated into its matrix some of the underlying solid formations while moving southward.

A short distance south of Limpsfield there is a gap in the Lower Greensand escarpment. Over the Weald Clay, which forms the low ground to the south of this, there is a dissected fan of Head, composed of flints and pebbles, similar to those of the Limpsfield Head, but with the addition of chert and other Lower Greensand fragments. This drift, which is not bedded and seldom over 2 or 3 ft. thick, extends as far south as Edenbridge. It has undoubtedly been derived mainly from the Limpsfield deposit. (*See* Text-fig. 6.)

To the south of the Lower Greensand escarpment, and usually opposite gaps and embayments in it, isolated patches of Head, composed of angular chert fragments, extend from the base of the escarpment across the Weald Clay to the River Eden (*see* Spurrell, 1886). These are remnants of what must have been once an extensive slope of detritus and now only exist as thin dissected patches between the stream valleys that drain from the foot of the scarp. They contain no flints or pebbles but only, as might be expected, Lower Greensand detritus in a matrix of sandy clay.

South of Ightham, another gap in the Lower Greensand range, occupied by the River Shode or Bourne, also connects Holmesdale with the Medway Valley. To the south of this the Weald Clay is again covered with patches of Head which here, in addition to chert, contains also flints and a few pebbles. These entered the area through the gap, and were derived from gravelly deposits near Ightham. Traced along the flanks of the Strode Valley, across the Weald Clay, the constituents of this Head become more rolled and a crude stratification is developed as the Medway is approached, finally it grades into unmistakeable terrace deposits of that river.

Almost all the deposits on the Weald Clay are confined to the north of the Medway and Eden, and from their distribution there can be no doubt that the detritus travelled down from the escarpment towards the Eden-Medway Valley, and that it was an important contributor to the material which the rivers rolled and sorted to form their terrace.

Of the deposits described above, those on the escarpments are clearly older than those in Holmesdale and on the Weald Clay. The latter, also, from their dissected nature and elevation are definitely older than the river terraces. A still younger Head is present in the district in the form of accumulations in dry valley bottoms of the Chalk. Mapped in the Caterham area under the name of Loam with Chalk and Flints, a deposit, up to 10 ft. thick, derived from the adjacent valley slopes, floors some of the Chalk coombes and overlies the Dry Valley Gravel with mammalian remains. It usually extends down the valleys as far as the point at which bournes occasionally break out.

AGE AND ORIGIN OF HEAD

Mass movements of the surface layers of the earth under gravitational forces vary from large-scale relatively rapid landslips and avalanches to slow, almost imperceptible hill creep, and may be classified in a variety of ways (*see* Sharpe, 1938). Those falling within the slow-flowing category range from the feeble soil creep under a cover of vegetation in temperate lands to the sheets of rock waste that characterize broad areas under Arctic or sub-Arctic conditions.

In many low-lying sheets of Head there is no evidence of modification of their original constructional form by erosion, and no indication of any considerable alteration of the adjacent topography since their accumulation. Such spreads of rock waste have moved down gentle slopes in quantities that are inconceivable under present climatic conditions: they are clearly on a different scale of magnitude from any hill creep or related processes that are active to-day. Thus, for example, coarse deposits of unsorted and unworn flint gravel that are now, to all appearances, static and are not normally water-logged have moved and incorporated masses of clay and sand such as could not survive transportation under temperate conditions. They are, moreover, usually covered with growing vegetation, and occasionally with an accumulation of peat or other recent deposit, and are not moving or accumulating under present conditions. The only controlling factor that can have changed appears to be the climate.

All available evidence favours the view that the closest modern analogues of Head are the widespread sheets of rock-waste that are being formed by solifluxion processes in sub-Arctic and periglacial regions. A similar mode of transportation and accumulation under severe climatic conditions has been advocated for many of the deposits included in the term Head and this view of their origin is adopted here. It should be pointed out that in certain favourable situations Head may be forming under present-day climatic conditions. In this country, however, such recent formation represents a very small fraction of the deposits.

In regions of severe climate, disturbance of the surface layers by frost action tends to prevent the formation of a protective blanket of vegetation. The surface layers are commonly over-saturated with melt-water from snow or ice and are underlain by an impervious layer of permanently frozen subsoil or " tjale ". The processes of thawing and freezing, the looseness of texture consequent on volume changes associated with these, and the presence of much interstitial water all favour bodily creep or flow of material to lower levels even on quite gentle slopes.

The Pleistocene deposits in Britain and the associated faunas are generally considered to indicate alternations of severe and relatively mild climate, and a recurrence of periglacial conditions favourable to the formation of extensive solifluxion deposits could reasonably be postulated. Just as glacial deposits are found in various stages of weathering and dissection depending on their age so the Head formed under cold climatic conditions is also found in a variety of situations and in different stages of weathering and dissection (*see* Breuil, 1934). Although it is not within the scope of this paper to develop a systematic age-classification of the Head throughout the country, it will be evident from the examples given that the older, weathered, hill-capping remnants of deeply-dissected sheets compare with the older glacial drifts (boulder clays, and sands and gravels, etc.), while the apparently unmodified deposits compare with the newer drifts where the constructional forms are but little if at all modified by subsequent erosion.

It is to be expected that each major increase in the severity of the Pleistocene climate in general represented by an advance of the ice-sheets would be marked by a peripheral belt on which Head formation took place. The presence of solifluxion layers in Pleistocene deposits thus forms a valuable clue to the elucidation of Pleistocene chronology (*see* King and Oakley, 1936).

As, however, the newer glaciations were in general less extensive than the older ones the regional distribution of their corresponding solifluxion deposits will be different.

Hence we find that the old dissected Heads are largely restricted to the south of England whereas the newer Head occurs much farther north and overlies, and frequently incorporates deposits of the earlier ice sheets. In the mountainous areas where the remnants of the ice sheets survived longest, local Head, or its near relatives, screes, snow-talus ridges, felsenmeer, etc., was formed after active solifluxion had ceased in the lower ground, and on the highest ground to-day indications of the processes of active flowage of the surface layers under the action of frost are present.

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The Geology of the Oil-field Belt of S.W. Iran and Iraq.[1]

By G. M. Lees and F. D. S. Richardson

I. INTRODUCTION

THE Near East is steadily growing in importance as an oil producing region. Present annual production-rates in the various countries are (in round figures) as follows . S.W. Iran 10,000,000 tons, Iraq 4,000,000 tons, Bahrein and the N.E. coast of Arabia 1,000,000 tons, Egypt 600,000 tons. In addition, recently discovered oil-fields are being developed, and active exploration of extensive areas is proceeding in these countries and in Syria, Palestine, and Sinai. The oil possibilities of this immense region are, naturally, not of equal order throughout, but a success in one area draws attention to all geologically related provinces, at least for first-stage exploration.

This article describes the main geological features of the most important of these oil-producing provinces, the oil-field belt of S.W. Iran and Iraq. Except in the alluvial plains, geological exploration in these countries is facilitated by the remarkably favourable natural conditions—the high relief, the general absence of superficial deposits, the great scale of the folding, the persistently distinctive appearance of the several members of the lithological succession, and the abundance of characteristic fossils in many parts of the sequence. Some 200,000 square miles of country have been surveyed by the geological staffs of the Anglo-Iranian Oil Company, Ltd., and the Iraq Petroleum Company, Ltd. Most of this area has been mapped on the scale of 4 miles to the inch, a scale which is suitable for rapid work and which at the same time allows the significant features of the structure to be brought out clearly. In the oil-field belt itself, many thousands of square miles have been mapped on the 1 in. scale, and larger scales have been used in selected areas.

II. REGIONAL STRUCTURE

The oil-fields of S.W. Iran and Iraq are situated in the foothills of the Zagros ranges. The mountain-country and the foothills together occupy a sector of the southern or Dinaride branch of the vast orogenetic system which extends from the Alps to the Himalayas; within this sector the rocks were strongly folded on a great scale during the later stages of Tertiary times. The oil-fields of the Arabian littoral, on the other hand, are located on the gently folded margin of the stable foreland towards which the strong Tertiary folding-movements were directed.

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[1] Published by kind permission of the Chairman and Directors of the Anglo-Iranian Oil Company, Ltd.

The strong folding was the effect of compressive forces acting on a thick body of sediments deposited in a major geosyncline. From the northern corner of Iraq to the mouth of the Persian Gulf, a distance of 1,200 miles, sedimentary conditions within the deeper part of the geosyncline were, for long ages, remarkably uniform at any one period; during the later Tertiary, however, the sea withdrew towards the S.E. end of the geosynclinal area, and deposits of Siwalik type became increasingly widespread. It is dominantly a calcareous province; the great mountains are formed by various thick limestone-groups ranging in age from Permian to Lower Miocene, and even the intercalated argillaceous groups are notably limy.

From the structural point of view, the foothills region and the greater part of the mountain-country may be grouped together as the *Normally Folded Zone*. This zone is occupied by extremely elongated anticlines and synclines of great size and amplitude arranged in sub-parallel lines, much as in the French Jura but on a considerably larger scale; the dominant trend of the fold-axes is N.W.–S.E. Near its N.E. margin the zone includes some great fault-slices, which have apparently developed from simple folds,[1] and also incorporates structures which were folded in Upper Cretaceous times and re-folded during the Tertiary.

The N.E. part of the mountain-country is occupied by great overthrust sheets, whose complex structure and irregular topography are in striking contrast with the bold and simple fold-mountains prevailing farther south-west. The lithological development, too, differs in important particulars; it includes certain elements comparable with those found in the Dinarides of S.E. Europe—great masses of basic igneous rock, both intrusive and extrusive (cf. the Ophiolite Zone), and a thick series of red and green radiolarian cherts and siliceous and calcareous shales ranging in age from Upper Triassic to Middle Cretaceous. The N.E. part of the Zone of Overthrusting is largely occupied by metamorphic rocks of unknown age—schists of various types and intensely sheared crystalline limestones; in places this complex is thrust right across the radiolarian chert element on to the edge of the Normally Folded Zone.

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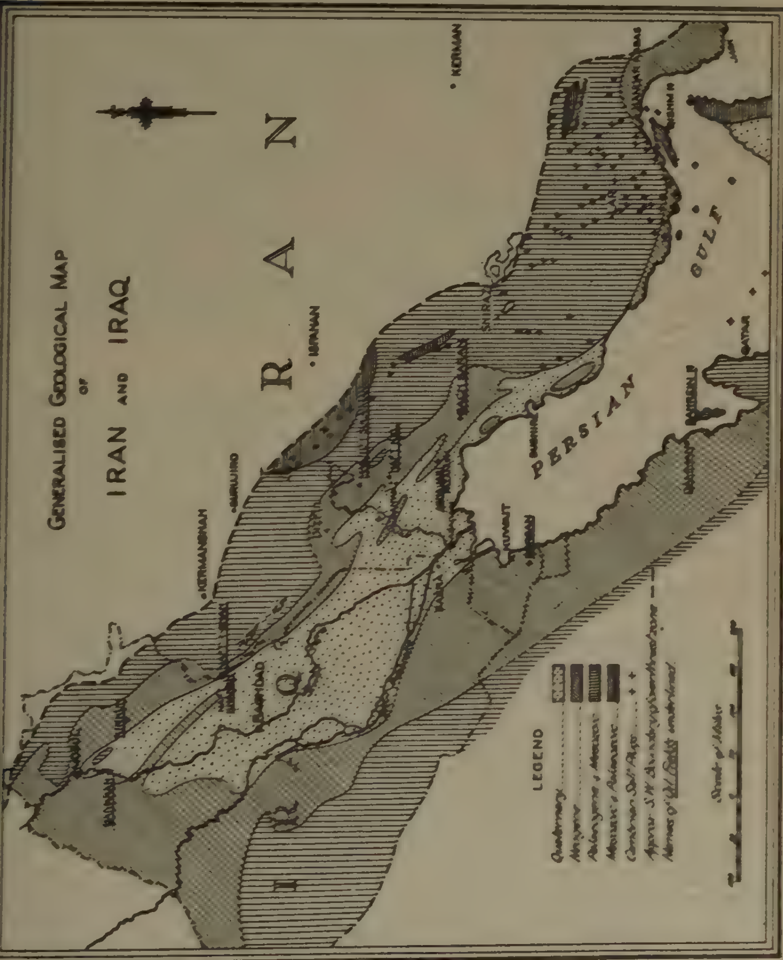
[1] These elements were formerly considered by de Böckh and the writers (1929) to belong to the Zone of Overthrusting, but later evidence has shown this interpretation to be incorrect.



North-east of the Zagros ranges lies the high plateau of Central Iran, flanked on the north by the Elburz mountains, which occupy a sector of the northern branch of the Alpine-Himalayan system. The plateau-country was described by de Böckh and the writers (1929) as a Zwischengebirge or Median Mass, i.e. a relatively resistant block lying between the two strongly compressed branches of an orogenetic system (cf. the Pannonian Basin). Nevertheless, its history has been a very disturbed one. The region is compounded of a number of distinct basins separated by uplifted areas ; in some parts great thicknesses of sediments have been deposited, in others defective sequences with violent unconformities are the rule. The rocks have been strongly folded at several different periods ; in contrast with the uniform trends of the Zagros and Elburz ranges, the fold-axes show no dominant direction, but tend to run parallel to the margins of the larger basins. During Tertiary times there was widespread volcanic activity on a great scale ; granitic intrusions of uncertain age also occur. A structural synthesis of Central Iran has yet to be undertaken, but on the stratigraphical side a noteworthy advance has recently been made with the publication by F. G. Clapp (1940) of the geological results of an exploration for oil in Northern and Eastern Iran.

Before leaving the subject of tectonics, we may refer to the important local effects produced by movements of salt.

In S.W. Iran and in the Gulf islands there occur numerous salt-plugs, great cylindrical intrusive stocks, with an average diameter of 3 to 4 miles ; their structural and stratigraphical features have been described by J. V. Harrison (1930). The age of the salt is Cambrian, and the plugs have forced their way up through the overlying strata until, in many instances, they tower above the surrounding country. Most of them occur in anticlinal folds, but many are located on a flank or on a pitching end, and there are even some in synclinal areas. Where the country rock is massive limestone it is little disturbed around the plug, but soft sediments such as the younger Tertiaries are often steeply upturned against the margin of the salt-body ; in several other countries important oil-accumulations occur in the upturned rocks around salt-plugs, but in Iran the structural effects of salt-plugs are small compared with the large normal folds among which they occur. A few of the plugs are known to have reached the surface in Upper Cretaceous or in Eocene times, but the most active period of uprise seems to have started during the Upper Tertiary. Many of them are inferred to be rising still ; great upstanding mountains of salt, up to 6,000 feet in height, are of common occurrence, and local earth-tremors and rumblings have been noted near some of them.

In Central Iran a large salt-plug occurs near Qum, and a few smaller ones have been observed in various places. They pierce younger Tertiary sediments, but it is not known how much older the salt may be.

Salt-movements of a different type are characteristic of the Miocene Lower Fars Series, which overlies the oil-bearing limestone throughout the foothills region. Salt is irregularly distributed through the greater part of this Series, which is known to be 4,000 feet thick in one or two places and may be much more elsewhere. While the major folding-movements were in progress, salt-flowage occurred on a vast scale, and resulted in the formation of a variety of extremely disharmonic structures, including large overfolds and overthrusts. So far did this process go that in a number of areas even the broad general structure of the surface beds is utterly different from that of the bold and simple folding of the oil-bearing limestone and older formations. This subject will be discussed further in a later section.

III. Stratigraphy of the Normally Folded Zone

Considerations of space make it necessary for us to confine our stratigraphical description to this tectonic zone, which includes the oil-field belt of S.W. Iran and Iraq. The outstanding features of the succession in this zone may be summarized as follows [1] :—

Pre-Cambrian.—No exposure known, unless the beds assigned to the Cambrian are partly older.

Cambrian.—Dominantly chemical or red sandy sediments, deposited in an area of rapid subsidence. In the S.E. thick salt-deposits, followed by U. Cambrian red and green shales, sandstones, thin dolomites, and limestones (trilobites, etc.) ; greatly disturbed (salt-plugs), and original thickness unknown. In the N.E. mainly red shales and sandstones (evidently derived from mountains uplifted in late Pre-Cambrian or early Cambrian times), with thin dolomites and limestones, some gypsum and traces of salt, followed by U. Cambrian as above ; up to 7,000 feet exposed. In the N.W., Cambrian rocks are not exposed.

Ordovician to Carboniferous.—Very poorly developed, largely shaly and sandy ; quiet conditions seem to have prevailed, with very little subsidence. In the S.E. : *Ordovician* (?), shales and thin sandstones with fucoids, 500 feet +, followed by quartzite, 60 feet; *Silurian*, graptolite-shales (probably L. Valentian), 200 feet; *Devonian* (?), sandstone with shale bands (*Spirifer ? verneuili* near base), 400 feet; *Carboniferous*, limestones with productids (probably U. Carboniferous), 50–200 feet. In the N.E., *Ordovician—L. Carboniferous* missing; *U. Carboniferous* (?), sandstones and plant-bearing shales (not older than Westphalian, possibly L. Permian), exceptionally 1,600 feet, usually less than 100 feet, resting concordantly on U. Cambrian.

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[1] Much new evidence, relating particularly to the development of pre-Cretaceous formations, has been obtained since the description by de Böckh and the writers was published.

Permian to Middle Cretaceous.—Dominantly limestones and dolomites, with anhydrite-bands appearing locally at several horizons. Marls or limy shales with thin-bedded limestones appear as a notable alternative facies in Triassic, Jurassic, and L. Cretaceous, and are very widespread in Aptian-Albian; from Jurassic onwards they are largely bituminous (black *Posidonomya* shales in Jurassic, dark brown marls with planktonic foraminifera in Cretaceous). Fossil-evidence indicates the presence of Permian (fusulinids), certain zones of L., M., and U. Triassic (mollusca) and L., M., and U. Jurassic (ammonites), also L. and M. Cretaceous (ammonites, etc.); owing to scarcity of fossiliferous bands, the Triassic and Jurassic are usually difficult to delimit, and it is not known whether lacunae exist in them; the L. and M. Cretaceous are fully represented. Approximate maximum thicknesses are: Permian, 3,000 feet; Triassic, 4,000 feet; Jurassic, 3,000 feet; L. and M. Cretaceous, 5,000 feet.

These formations were deposited in a great subsiding geosyncline which extended laterally beyond the N.E. limit of the Normally Folded Zone. The presence of basic igneous rocks and of a very thick Triassic-Cretaceous radiolarian chert series in the Zone of Overthrusting suggests that the deepest part of the geosyncline lay on that side.

Upper Cretaceous and Eocene.—Dominantly bituminous marls and thin-bedded limestones, with planktonic foraminifera; limestones appear as an alternative facies, and become widespread in M. and U. Eocene times; anhydrite is thickly developed locally in L. Eocene (in the S.E.), and some bands occur higher up in places. Both U. Cretaceous and Eocene are fully represented in most places (foraminifera, etc.).

Major folding-movements took place along the N.E. margin between Turonian and Maestrichtian times, and further movements seem to have been in progress during Maestrichtian and part of Eocene times. On this side the Maestrichtian becomes strongly transgressive, and both it and the Eocene include thick masses of sand and conglomerate, largely derived from the basic igneous rocks and radiolarian cherts which occur farther north-east. One effect of the folding-movements was to displace the deeper part of the geosyncline a considerable distance to the south-west, to a position well within the Normally Folded Zone. Subsidence continued, but from Middle Eocene times onwards it failed to keep pace with sedimentation; nummulitic limestones spread far into the basin, from both sides, and the area occupied by foraminiferal marls showed a corresponding contraction.

Maximum thicknesses of the U. Cretaceous are 5,000 feet in the normal marine facies, and over 10,000 feet where the clastic facies is developed; the Eocene shows similar thicknesses.

Oligocene and Lower Miocene (part).—Lower part *Globigerina*-marls, alternatively nummulitic or orbitoidal limestones; higher part dominantly limestones with other benthoic foraminifera; important anhydrite-intercalations develop over wide areas at more than one horizon, and even salt occurs locally; in one place, near the mouth of the Persian Gulf, limestone is wanting entirely, and only marl and anhydrite are present. In the N.E., red sandy or conglomeratic beds occur extensively, but do not attain great thicknesses. Fossils consist largely of foraminifera, and a number of local faunal zones have been established with their help. The maximum thickness of the Oligocene-L. Miocene deposits is about 2,500 feet.

During this period of deposition, subsidence again failed to keep pace with sedimentation, and limestones eventually spread into the deepest part of the geosyncline. Some movement took place at the end of Eocene times in the S.E., where the Oligocene rests unconformably on M. Eocene in many places. The beds which succeed the Oligocene nummulitic limestone in the extreme S.E. are difficult to correlate with those deposited farther N.W., and there is some reason to think that connection between the main part of the geosyncline and the open sea may have been restricted, perhaps by a shallow-water platform situated opposite the middle part of the Persian Gulf; this part of the country, however, is little known at present, and the matter awaits investigation.

In N.E. Iraq, and in the adjoining part of Iran, some movement occurred very early in Miocene times, resulting in regression and erosion, and the entry of conglomerates into the basin; this phase was followed by a transgression near the end of the period.

The limestone-series, which is the dominant representative of this period of deposition, is the oil-producing formation in the fields of S.W. Iran, where it is known as the *Asmari Limestone.* The age of its lower limit varies considerably; its thickness (in the oil-fields) ranges up to 1,500 feet. At Kirkuk, in Iraq, the oil-producing limestone is mainly Eocene and Oligocene, the L. Miocene part being greatly reduced.

Lower–Middle Miocene (underlain by Burdigalian, overlain by M. Miocene). *The Lower Fars Series.*—Dominantly chemical, varying towards red sandy deposits. Normal facies:—Alternating grey marls, anhydrite and salt, with subordinate thin foraminiferal and shelly limestones, red marls, and some bituminous shales. As in the preceding series the beds in the extreme S.E. are difficult to correlate with those found farther N.W., and the persistence of a shallow-water platform opposite the middle of the Persian Gulf is inferred; the periodical emergence of such a barrier could account for the conspicuously cyclic precipitation of salts within the main part of the geosyncline; it is also noteworthy that the commencement of chemical deposition appears to have been virtually simultaneous throughout the main basin.

Rapid subsidence went on while the Lower Fars was being deposited. In Iraq, on the N.E. margin, the lower members of the series display north-eastward overlap, representing the continuation of the transgression which set in after the L. Miocene movement; in Iran, N.E. of the Masjid-i-Sulaiman oil-field, the middle part of the series shows a similar overlap, and the preceding movement occurred later than in Iraq. The marginal overlap was followed by a south-eastward withdrawal of the sea, which (though it was accomplished gradually, and with numerous oscillations) had attained great proportions by the end of the period; at the same time, the deepest zone of the trough became displaced towards the S.W. Red and sandy material from the N.E. spread increasingly far into the basin, and in Iraq the higher part of the series consists wholly of red marls and sandstones indistinguishable from the succeeding formation. It is inferred that folding-movements were in progress on the N.E. side. A certain reduction in maximum concentration of the sea-water near the end of the period is indicated by the complete absence of salt in the highest beds.

Within the chemical basin the degree and rate of lateral variation is phenomenally small, and detailed correlation has been effected over wide areas, with the help of foraminiferal faunules and of crystalline inclusions of various minerals in anhydrite-bands.

Owing to the widespread disturbance of the Lower Fars, its original thickness can seldom be determined ; in one or two places it is known to be 4,000 feet, but it may have been much more elsewhere. Important unconformities at various horizons have been suspected at a number of places within the chemical basin, but only where intense disturbance has taken place ; in the few places within the basin where the series is relatively undisturbed, neither unconformities nor lacunae can be detected.

Middle–Upper Miocene and Pliocene.—Dominantly red and sandy, with conglomerates entering in higher part ; varies towards marine facies in the S.E. The south-eastward withdrawal of the sea continued on a great scale, though gradually and with many oscillations ; red and coarse sediments spread increasingly far into the basin, and it is only in the extreme S.E. that the series is essentially marine throughout. In the S.E. generally, e.g. around the Gach Saran oil-field, the series begins with a Middle Miocene marine group, the Middle Fars, which consists of grey marls with limestones, including algal and other reefs [1] ; large mollusca abound, chemical deposits are wanting entirely, and it is evident that free connection with the open sea had been restored ; maximum thickness exceeds 3,000 feet. In the N.W. these beds give way to red sandy sediments which are indistinguishable from those that follow, and which are there included in the *facies-group* known as Upper Fars. The remainder of the series in the S.E. consists of alternations of red sandy sediments and marine grey marls with thin limestones and some anhydrite-bands ; conglomerates become increasingly important in the higher parts, particularly in the N.E. ; near the present Gulf Coast a local marine incursion at the end brought in a thin group of marls and limestones with *Pecten vasseli* Fuchs.

Farther N.W. marine beds are wanting entirely, and red marls or silts, with coarse sediments, extend throughout ; thin fresh-water limestones and grey marls occur sporadically. The following facies-groups are distinguished, but have no precise connotation. *Upper Fars :* red marls, silts, and sandstones, with little gritty material. *Lower Bakhtiari :* lower part more silty and more gritty, locally some anhydrite-bands with fresh-water marls ; higher part (sometimes separated as Middle Bakhtiari) again coarser, with bands of conglomerate derived from the N.E. margin, or alternatively from the Fars cover of neighbouring folds. *Upper Bakhtiari :* coarse limestone-conglomerates derived from the nearer ranges, also silts and conglomerates with local material. L. Pliocene indicated by very rare vertebrates (*Hipparion*) in beds assigned to lower part of L. Bakhtiari ; no further age-control. Full thickness exceeds 12,000 feet.

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[1] Where this facies is not developed, the name Middle Fars has in the past been applied to beds which are now known to belong to the higher members of the Lower Fars.

The main folding movements took place during this period. The geosynclinal area underwent rapid subsidence, and received increasing quantities of detritus from the folds which were rising in the N.E. ; the deeper zone first shifted south-westwards, and later became divided into a number of synclinal basins, as the folding developed.

The history of the folding movements is very incompletely known. Near Gach Saran the Middle Fars thins rapidly towards the N.E., and is overstepped in the same direction by beds belonging to the lower part of the succeeding series. The Lower Bakhtiari commonly shows rapid thickness-variation on a great scale, marking the development of local basins, whilst the Middle Bakhtiari shows well-marked overlap, developing into a very important unconformity in many places, though in the deep local basins no break is discernible. The Middle Bakhtiari (and possibly some older beds, too) in places contains quantities of inspissated oil and detrital bitumen, derived from neighbouring anticlines in which the Asmari Limestone must have been at or near the surface, and this (together with the great thickness-variations in the Lower Bakhtiari) indicates that the folding movements had already attained formidable dimensions. An unconformity of some importance is frequently present at the base of the Upper Bakhtiari, and at least one other develops locally within this group. The final phase of the main folding movements took place after the deposition of the Upper Bakhtiari, and is presumed to be late Pliocene in age.

There are some curious features connected with the development of the folding-movements. In some places the Lower Bakhtiari thinning and the Middle Bakhtiari transgression are directed towards existing anticlines in the pre-Fars formations ; in other places, however, they are directed towards large-scale disharmonic Lower Fars structures which were already in existence (though not completely developed) at the time of the transgression, and beneath which, according to geophysical evidence, the pre-Fars formations now lie at great depths and are not anticlinally folded. Another curious feature is that many of the Bakhtiari basins are now strongly tilted towards the N.E., the thin edge being relatively depressed and the thick part being strongly elevated. It seems likely that the existing fold-pattern in the pre-Fars rocks of the foothills region developed at a late stage in the folding-movements. There is some reason, too, to suspect that the dominant N.W.–S.E. trend of the folding was imposed at a comparatively late stage, and that the earlier fold-trends followed a more sinuous course.

Pleistocene and Holocene.—Raised beaches, high-level gravels, river-terraces, scree-fans, alluvium of the plains, etc. Minor movements continued into Pleistocene times ; the rise of some of the salt-plugs is believed to be still in progress at the present day.

Igneous Rocks.—Many of the salt-plugs bring up igneous rocks of unknown age (quartz-keratophyres, dolerites, etc.) ; these have been described by Harrison (1930). Apart from these, no igneous rocks exist in the Normally Folded Zone of S.W. Iran and Iraq, though they are strongly developed farther N.E., in and beyond the Zone of Overthrusting.

IV. MODE OF OCCURRENCE OF THE OIL

The genesis of an oil-field demands the fulfilment of four distinct conditions ; there must be (*a*) source-rocks within which oil can be formed, (*b*) reservoir-rocks which are able to store it in quantity and deliver it into wells, (*c*) impervious cover-rocks which can prevent its escape to the surface, and (*d*) sufficient structural deformation to cause it to accumulate locally.

The oil which occurs in the fields of S.W. Iran and Iraq is thought to have originated in the deep-water marls which were laid down during Mesozoic and Palaeogene times. These are predominantly chocolate-brown to blackish in colour (characteristically weathering pale blue or white), and they contain up to 15 per cent, by weight, of adsorbed hydrocarbons. This bituminous, or polybituminous, material is only slightly soluble in chloroform or carbon tetrachloride ; on destructive distillation, however, a strong yield of oil is obtained from some zones, though others only yield gaseous hydrocarbons and a coke-like residue. Veins of hard brittle bitumen are commonly present in the marl-outcrops throughout the mountain-country, and many oil-seepages issue from these rock-groups. Fossils consist largely of planktonic foraminifera ; benthoic forms include *Posidonomya* (in the Jurassic), and Spatangidae (in the Palaeogene) ; ammonites (planktonic or benthoic ?) occur in the Jurassic and Cretaceous ; microscopic organisms of uncertain affinity (algae ?) are frequently present in quantity ; the presence of pyrite is noteworthy. The marls show remarkably even bedding, testifying to the absence of current-action, and it is evident that they were laid down in a stagnant deep-water milieu deficient in light and oxygen. Similar conditions exist to-day on the floor of the Black Sea, where black evil-smelling sulphidic mud, with a high organic content, is being deposited ; it is interesting to note that in the Gulf of Oman, beyond the mouth of the Persian Gulf, similar sediments are being laid down.[1] Under such conditions the normal processes of decay would not be fully operative, and it is inferred that much of the organic content of the marls escaped destruction and dissipation, and was later transmuted into the complex assemblage of solid, liquid, and gaseous hydrocarbons (paraffins, olefines, naphthenes, etc.) which goes by the name of petroleum. The processes by which this transmutation was effected are, as yet, far from being understood.

The reservoir-rock in the fields of Iran and Iraq is the limestone-group which directly underlies the Lower Fars chemical series ; in Iran this is the Oligocene - L. Miocene Asmari Limestone, whilst at Kirkuk in Iraq the limestone-phase extends well down into the Eocene and the L. Miocene part is greatly reduced. The fact that the reservoir-rock has been able to receive oil in quantity is due to the intensity of the folding-movements ; the brittle marls and thin limestones down below were effectively broken up by a network of cracks, whilst a great joint-system developed in the limestone itself, opening the way to the various porous zones within it. The fact that the oil has remained in the reservoir-rock, instead of escaping to the surface, is due to the lithological qualities of the Lower Fars Series ; owing to the plasticity of the salt and saliferous marls, and to the impermeability of the anhydrite-bands, this series constitutes a generally effective seal ; it is not a perfect seal, however, for gas-escapes occur at the surface in all the known fields, and oil-seepages in many of them.

The oil has accumulated in the higher parts of huge elongated anticlinal domes, of great amplitude and large independent closure, whose steeper S.W. flanks show dips varying between 20 and 70 degrees. The oil-filled parts of these domes are, in several instances, 10 miles or more in length, 1 to 3 miles in width, and 1,000 feet or more in depth, with a limestone-volume of some cubic miles ; even so, they are small by comparison with the surrounding territories from which the oil has migrated into them.

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[1] Described by R. B. Seymour Sewell (1935).

The highest part of a dome is usually occupied by gas; in some places the original gas-zone is extremely small, but in others it has a depth of several hundred feet, and in one instance 2,000 feet. Below this comes the zone of oil, which is saturated with gas in solution, and below that again salt water is found. The water extends into and through the synclinal areas, and beyond them as far as the mountains where the Asmari limestone rises to the surface. Water is heavier than oil, and the weight of the column of water on the side where the limestone outcrops is considerably greater than that of the column of water, oil, and gas within the dome; for this reason, oil or gas which is encountered in a well will flow to the surface without being pumped. The differential pressure exerted by the external water-column is often very large; in a number of fields the pressure recorded on the surface-fittings of closed-in gas-wells exceeds 1,000 lbs. per square inch; in one field, where the limestone lies at a depth of 3,000 feet, a gas-pressure of 2,600 lbs. per square inch has been measured.

When oil is extracted from the reservoir-rock, the weight of the local fluid-column is correspondingly reduced, and this causes water from outside to enter the dome. In practice it is found that the rate at which external water is able to enter is much smaller than the rate at which oil is generally extracted; the consequence is that the greater part of the space vacated by oil becomes filled by gas released from solution, and whilst the oil-water level rises slowly, the gas-oil level descends much more rapidly. This is a matter of considerable economic importance, since the trapping and contamination of oil by the rising water is greatly restricted.

The oil occurs partly in pore-spaces within the limestone-rock itself, partly in the joints and cracks which traverse it. The degree of porosity accords generally with the extent to which the rock has been recrystallized,[1] and varies considerably from zone to zone and from place to place; in some fields the limestone is mostly dense, with a small minority of porous bands, whilst in others porous zones of great thickness occur. When the pressure in the reservoir-rock falls, owing to the extraction of oil, some of the gas contained in solution is liberated in the pores, and oil is gradually expelled into the cracks and joints, providing what is probably a very important addition to the oil originally contained in them; in a well, however, the superficial area of rock-face is so small, relatively speaking, that in the absence of joints even the most porous zones will not yield oil in important quantities. It is from the larger joints that the productive wells draw their oil ; these form a network throughout the anticlinal folds, and many of them are seen at outcrop to traverse the whole thickness of the limestone-group and to extend for long distances. Their spacing varies considerably within the limits of a single field ; in some parts nearly every well will meet with large joints in the topmost part of the limestone, in others it will often be necessary to drill through hundreds of feet of it before a single one is encountered. The rate at which oil will flow from a joint is often very high, and in a number of instances exceeds 1 million gallons a day ; it has been calculated that, in order to yield a flow of this magnitude under the prevailing pressure-conditions, the space between the two walls of a joint need not be more than a few millimetres wide.

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[1] It has not been found possible to establish a direct relationship between porosity and dolomite-content.

The freedom of fluid connection within the joint-system is such that the pressure-drop induced by withdrawal of oil is rapidly transmitted throughout the field ; if oil is drawn from a group of wells in one part of the field, the effect will in a surprisingly short time be perceived in a pressure-observation-well many miles away. This makes it possible so to regulate output, adjusting the rate of withdrawal from each sector of the field to its observed productive capacity, that the fall in pressure shall be evenly distributed and local disturbance of the fluid-levels avoided.

In two of the Iranian oil-fields the Middle Cretaceous Limestone has been drilled into, but has proved to contain only water in its joint-system, though oil is present in the pores of the rock. The reason appears to be that the overlying marls and thin limestones of the Upper Cretaceous and Palaeogene do not function as effective cover-rocks when they are so strongly folded ; they are sufficiently hard to allow the development of a system of open cracks and small joints through which fluid connection is maintained, and it seems that the bottom-water of the Asmari Limestone reservoir is continuous downward into the core of the anticline to an unknown, but very great, depth. Upward migration of oil through the water in the joint-system may have taken place through many thousands of feet of strata, and the existing oil accumulations in the Asmari Limestone, beneath the impervious Lower Fars cover, may be derived from several members of the stratigraphical sequence, each of which has contributed its quota.

Conditions are different in the broad gentle domes of the

Arabian littoral ; here the various marly groups are at once softer and much less fractured, and they form effective cover rocks to oil-accumulations which occur in porous limestones or sands of Middle and Lower Cretaceous, and perhaps Jurassic, age.

V. DISTRIBUTION OF THE OIL-FIELDS

The existing oil-fields are all situated in the foothills, where the limestone anticlines are covered by Lower to Upper Fars rocks, with the Bakhtiari beds occupying the synclines. The width of the foothills zone varies greatly. In Northern Iraq the edge of the mountain-country lies far back towards the north-east ; farther south-east it swings forward for a considerable distance, following the Iranian frontier, and the Pusht-i-Kuh mountains (east of Baghdad) rise almost directly from the Iraq plains, with only a very narrow belt of foothills in front of them ; farther south-east again, the edge of the mountains swings back once more, and a wide zone of foothills develops, extending to the neighbourhood of Bushire ; beyond here the mountain-front again swings forward, and along the rest of the Gulf Coast there is only a narrow and discontinuous zone of foothills. The markedly sinuous course of the mountain-front is only to a small extent due to variations in the trend of the folding ; it is primarily due to alternating regional culminations and saddles in the fold-system (Haug's " aires de surélévation et d'ennoyage ").

In the search for oil-fields, attention has naturally been concentrated on the two areas where the foothills zone is wide and includes a large number of anticlines in which the thickness of the cover-rocks is sufficient, yet not excessive. These areas lie, respectively, in the Khuzistan province of Iran, N.E. of the head of the Persian Gulf, and in Northern Iraq and the adjoining frontier-region of Iran. In the former area there are at present five proved oil-fields, at Masjid-i-Sulaiman, White Oil Springs, Haft Kel, Agha Jari, and Gach Saran. In the latter area there are two, Kirkuk and Naft Khaneh—Naft-i-Shah ; oil of a heavy sulphurous type has also been found in a number of places lying west of Kirkuk, e.g. at Qaiyarah, but under present market conditions its exploitation would not be profitable.

VI. SURFACE INDICATIONS OF OIL AND GAS

We have already mentioned, in Section IV, that the various bituminous marl-groups are very frequently traversed by bitumen-veins, and that in addition oil-seepages issue from them in a number of places. Many oil-seepages also occur along the outcrops of the Asmari Limestone. In this section, however, we are concerned rather with the surface-indications within the oil-field belt itself, where the Limestone is buried.

In many places up and down the country oil and gas issue, or have issued, from the rocks which overlie the Asmari Limestone. Active seepages of liquid oil are frequent, whilst inspissated residues occur widely in the form of bitumen-deposits and veins, impregnations in porous or shattered rocks, and heavy oil-staining in gypsum-bands.[1] Gas escapes, also, are of widespread occurrence; in a few instances they are accompanied by small quantities of natural kerosene, produced by condensation of the heavier fractions of the gas.

The presence, or former presence, of gas escapes is prominently marked by certain curious chemical changes in the surrounding rocks. One of these consists in the partial or wholesale replacement of bands of gypsum (or anhydrite ?) by porous crystalline aragonite or " secondary limestone ". This change cannot be perceived to be going on now, and it seems likely that it takes place below ground, where the rocks are waterlogged and reducing conditions exist. The mechanism of the change is not understood, but is suspected to be typified by the reaction $CH_4 + CaSO_4 = CaCO_3 + H_2S + H_2O$, a reaction which is claimed to have been demonstrated in the laboratory, albeit at a red heat.

Another of the changes consists in the replacement of limestone or marl by a curious mixture of substances known in Persian as Gach-i-turush (anglice " sour gypsum "). This mixture, which occurs in dark brown earthy masses with a white crust, consists largely of gypsum-crystals, associated with sulphur and free sulphuric and sulphurous acids (up to 9 per cent of free acids has been determined) and, not infrequently, jarosite and chalcedony; it is supposed that the acids are produced by the oxidation of H_2S, which is generally present in the gas, and that the principal reaction is $H_2SO_4 + CaCO_3 = CaSO_4 + CO_2 + H_2O$. The Gach-i-turush has a sour taste and also a strong characteristic smell, which is similar to that given off when sulphuric acid is placed on sugar and is doubtless due to the action of this acid on organic matter in the soil. It occurs in great patches around active gas-vents, and is certainly being formed on the surface at the present day.

A third change consists in the bleaching of red marl-bands to a grey or greenish colour, presumably by the reduction of iron from the ferric to the ferrous state ; in certain large gassy areas, a notably red group in the Lower Fars has been almost completely bleached through a thickness of several hundred feet. In the red Upper Fars deposits, which seem to be insufficiently limy to allow the formation of Gach-i-turush, bleaching to a green colour along joints is found in some areas, and it is thought that this marks the position of former gas escapes ; in one place some of these joints contain stringers of paraffin wax, though oil-staining is absent.

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[1] The anhydrite of the Lower Fars is hydrated to gypsum at and near the surface of the ground.

In a number of places where oil or gas has escaped to the surface, burnt rocks occur. The most remarkable occurrence is at Tul-i-Marmar, near the Gach Saran oil-field, where a considerable part of a large hill has been burnt ; the grey marls of the Middle Fars have been baked to a red colour and a hard tile-like consistency, and large masses of glassy and even crystalline rocks are also present [1] ; the adjoining valleys have been cut down by at least 20 feet since this great conflagration took place, and the marls underlying the burnt part are seen to be blackened with a coke-like oil-residue ; small oil-seepages still exist close by. Another burnt place, again with some crystalline rock, occurs in association with a large gas escape on the outskirts of the Agha Jari oil-field ; the gas is still escaping on a large scale, and there is a great area of Gach-i-turush around it.

These various surface-indications of oil and gas are a great help in the search for oil-fields. Gas escapes are associated with all the existing fields, and oil-seepages with four of them.

Many of the surface-indications are situated directly above the underground accumulations of oil and gas, but many others are not. Where the Lower Fars is strongly disturbed, and particularly where important overthrusting occurs, the escaping fluids are frequently conducted laterally along the bedding or along thrust-planes, and issue at points far removed from the oil-bearing part of the limestone fold ; in the Agha Jari field, for example, all the numerous gas escapes are associated with the emergence of a thrust-plane, and are displaced 3 miles across the strike from the nearer edge of the gas-area in the dome. Surface-indications are also frequent in and around one or two domes in which the limestone is already exposed but has not yet been completely drained of its oil and gas. A few exist in places where their presence cannot yet be satisfactorily explained.

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[1] The metamorphic rocks formed here and in other places have been described by W. F. P. McLintock (1932.)

VII. Structural Problems

In view of the great size and amplitude of the limestone folds it might have been expected that their location would be a simple matter, particularly in a terrain where first-class uninterrupted exposures prevail. In practice, however, their location by geological methods alone is often difficult, and becomes virtually impossible in certain areas. This difficulty is due to the disharmonic movements of the Lower Fars, which has behaved as a plastic medium between the limestone below and the relatively rigid masses of M. and U. Fars and Bakhtiari sediments above. So far have these movements proceeded, that even the major structural features of the outcropping beds are often only partly similar to those of the limestone, and are sometimes completely dissimilar.

In a few places, where the Lower Fars is thin and deficient in salt, the surface structure does conform more or less closely with that of the limestone. Most commonly, however, it is only on the N.E. limb that the structure of the limestone and of the surface beds is essentially similar. In these folds the Lower Fars and its cover have been driven south-westwards across the limestone anticline, and whereas on the S.W. limb the limestone descends more or less steeply, the surface beds continue to rise gradually for a considerable distance, and then either turn down abruptly into the fore-syncline or, more frequently, are thrust forward across its margin.[1] In the Agha Jari field, the anticlinal axis in the surface beds lies 3½ miles S.W. of the limestone axis, and the horizontal displacement of the subjacent overthrust is known to be not less than 1½ miles. In the Haft Kel field, the Lower Fars outcrop extends for a distance of 6 miles S.W. of the limestone axis; the fore-syncline is here buried under alluvium, and it is not known whether or to what extent overthrusting may have taken place.

In certain areas, where the Lower Fars is now widely exposed and where its freedom of movement has been less restricted by overburden, still more abnormal structures are developed, and there is no closely fitting N.E. flank in the surface-beds. In one

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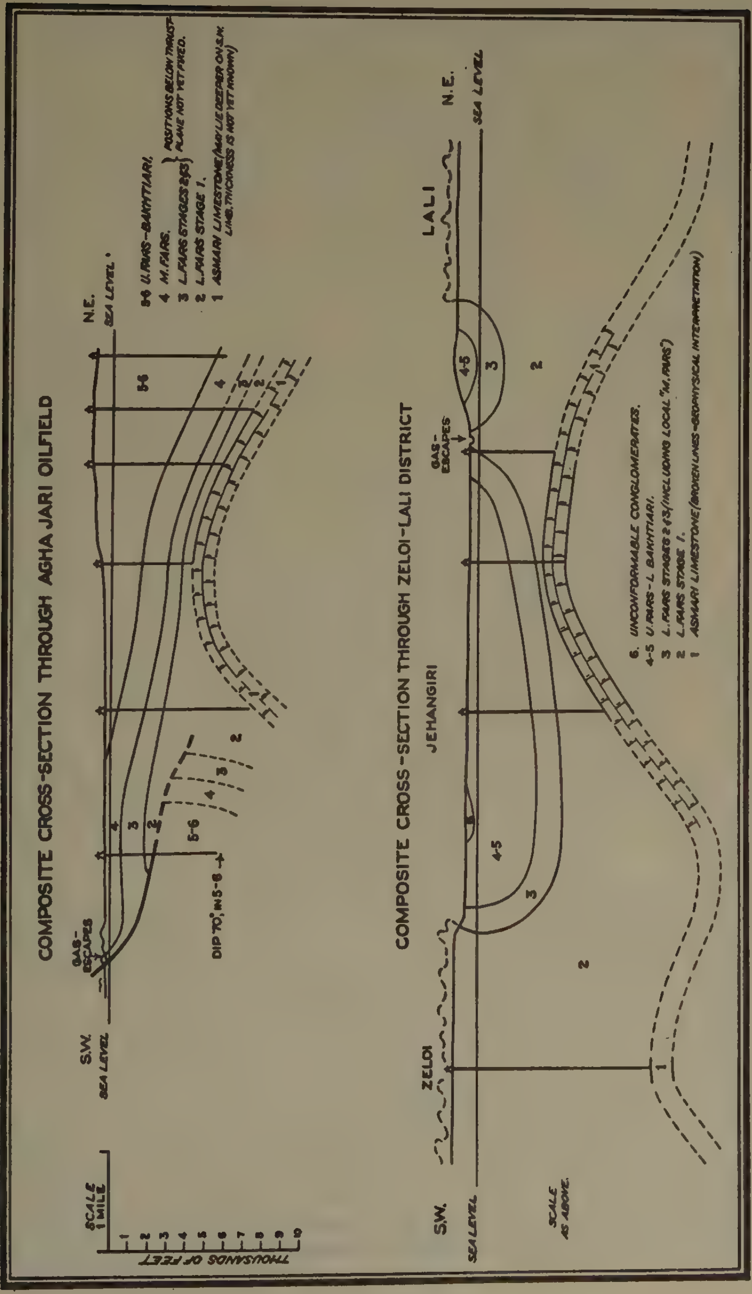
[1] The structure of the Kirkuk oil-field, which has been described by N. E. Baker (1938), is of this type.


COMPOSITE CROSS-SECTION THROUGH AGHA JARI OILFIELD
S.W.
SEA LEVEL
GAS-ESCAPES
N.E.
SEA LEVEL
5-6
4
3
2
1
DIP 70°, IN 5-6
5-6 U. FARS—BAKHTIARI.
4 M. FARS.
3 L. FARS STAGES 2 & 3
2 L. FARS STAGE 1.
1 ASMARI LIMESTONE (MAY LIE DEEPER ON S.W. LIMB. THICKNESS IS NOT YET KNOWN)
POSITIONS BELOW THRUST-PLANE NOT YET FIXED.
SCALE 1 MILE
1 2 3 4 5 6 7 8 9 10
THOUSANDS OF FEET
COMPOSITE CROSS-SECTION THROUGH ZELOI-LALI DISTRICT
S.W.
SEA LEVEL
ZELOI
JEHANGIRI
GAS-ESCAPES
LALI
N.E.
SEA LEVEL
6
4-5
3
2
1
6. UNCONFORMABLE CONGLOMERATES.
4-5 U. FARS - L. BAKHTIARI.
3 L. FARS STAGES 2 & 3 (INCLUDING LOCAL "M. FARS")
2 L. FARS STAGE 1.
1 ASMARI LIMESTONE (BROKEN LINES = GEOPHYSICAL INTERPRETATION)
SCALE AS ABOVE.

extreme instance the axial part of the limestone dome is overlain by a large U. Fars-Bakhtiari syncline, which is flanked by vast Lower Fars accumulations. In such areas the Lower Fars is itself thrown into a series of large and small folds, many of which are squeezed, faulted, diapiric, overturned, or overthrust. Since this type of structure extends through great areas of the higher foothills, and since it occurs both where limestone-anticlines exist and where they do not, the difficulties confronting the field-geologist may be imagined. Fortunately it is now possible to locate the limestone-anticlines by geophysical means.

The importance of the structural divergence between the surface beds and the limestone was only gradually appreciated ; indeed, it is only within the past few years that its full magnitude has been revealed, and we are still far from understanding by what processes it came into being. In a number of areas in which the surface-structure on the N.E. flank conforms with the limestone, the earlier exploration-wells were, as a rule, located too far to the south-west, in the higher part of the surface anticline, where the limestone is now known to lie at great depth ; the existence of the frontal thrusting was realized, but its magnitude was underestimated. In the great Lower Fars areas, on the other hand, several exploration wells were drilled on major surface anticlines or anticlinoria which, as we now know, are essentially Lower Fars accumulations, and beneath which the limestone lies at great depth and, in most instances, is not even anticlinally folded.

The history of exploration in the neighbourhood of the Masjid-i-Sulaiman oil-field is an interesting example of the way in which the magnitude of the structural problem was gradually revealed. At Masjid-i-Sulaiman the greater part of the oil-bearing limestone dome underlies a much broader Lower Fars anticlinorium, flanked on the N.E. and S.W. by major Fars-Bakhtiari synclines. Above one part of the oil-zone, where the cover is thinnest, there is a great development of oil-seepages and gas-escapes, with Gach-i-turush and porous aragonitic " secondary limestones " (i.e. replacements of gypsum-beds). The first well, which was successfully completed in 1908, was located among the most prolific group of seepages, on one of the small Lower Fars anticlines which, as we now know, are completely independent of the structure of the Asmari limestone. During succeeding years exploration continued, by a process of gradual feeling-out, until the greater part of the seepage-area had been covered. It so happens that in this part of the field the Limestone is profusely jointed, so that the early wells encountered oil in quantity in its topmost beds, and for this reason it was many years before the true identity of the reservoir-rock was realized[1]; during this period the oil was believed to be contained in the Lower Fars, in porous beds similar to the "secondary limestones" (whose secondary nature was not then appreciated), and lenticularity was invoked to account for the impossibility of deducing, from the surface structure, the depth at which oil would be struck.

After this stage exploration proceeded at an increasing rate until, by 1929, the whole oil-field had been delimited. It was found that, towards the north-west, the limestone dome extended for several miles beneath a great Upper Fars synclinorium, its course being indicated by a well-marked anticlinal fold in the surface beds; the synclinorium is separated from the major synclines on the N.E. and S.W. by relatively narrow Lower Fars accumulations of great depth. Above this part of the limestone dome the Lower Fars is very greatly reduced; the presence of salty breccias and severely contorted anhydrite indicates that strong movement of the overburden is at least partly responsible, and it is noteworthy that farther to the south-west an important overthrust develops; whether unconformities have also played a part is at present unknown.

North-west of the Upper Fars synclinorium, in the *Zeloi* district, there is again a broad anticlinorium of Lower Fars, similar to that which covers the greater part of the Masjid-i-Sulaiman dome; it is flanked on the S.W. by a major syncline, and on the N.E. by the syncline of *Jehangiri*, a smaller but still large structure, whose central part is occupied by Lower Bakhtiari beds which are stratigraphically higher by some 7,000 feet than those occupying the surface at Zeloi. Surface-indications of oil and gas are wanting in the Lower Fars of Zeloi, but so they are over the greater part of the Masjid-i-Sulaiman field itself. It was considered that there ought to be a large limestone anticline at a reasonable depth in the Zeloi area, and three wells were drilled there in 1926 and succeeding years; none of these, however, succeeded in reaching the limestone. Some years later a geophysical survey indicated the presence of an anticlinal axis in the limestone near the old wells. A fourth well was accordingly drilled, during 1936–37; the limestone was reached at a depth of nearly 10,700 feet, but proved to be waterlogged. The strata overlying the limestone belong exclusively to the middle and lower portions of the Lower Fars (known collectively as Stage I), and the vertical depth of these deposits, including those beds which have been eroded away, is fully 11,000 feet at this point ; detailed correlation is difficult in this area, and it is impossible to say what proportion of this abnormal thickness is due to steep dips, repetition, and the swelling-out of beds during plastic flow into a relatively low-pressure area.

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[1] The fact that it is the Asmari Limestone was demonstrated by Professor S. J. Shand, who visited the country on behalf of the Anglo-Persian Oil Company, Ltd., in 1919.

When it became evident that the fourth well was going to be very deep, attention was directed towards the *Lali* district, which lies farther north-east, beyond the Jehangiri Syncline. At Lali there is again a large anticlinorium of Lower Fars, whose N.E. margin is overthrust on to high Bakhtiari deposits, as was already known. Geological and geophysical work proceeded simultaneously. First of all the main Lower Fars area was examined ; the geological findings stressed the importance of the north-eastward overthrust, and suggested that the limestone anticline, if any existed, should lie towards the south-west, near the Jehangiri Syncline ; the geophysical evidence indicated that beneath the Lower Fars area the limestone lay at excessive depth and was not anticlinally folded. A move was accordingly made to the south-west. Here the geophysical evidence at once revealed the presence of a large limestone dome lying beneath the Jehangiri Syncline itself, though N.E. of its deepest part. Even with this knowledge, the geological examination failed to reveal any surface indication of the presence of the dome, apart from a suggestive S.W. dip in some unconformable conglomerates situated above the S.W. flank of the limestone fold, and a few small gas escapes marked by Gach-i-turush ; some of these gas escapes had been noted many years previously, but in view of their unattractive structural position little importance had been attached to them.

As a result of this survey, a well was drilled in 1937–38 on the axis of the dome, as defined by the geophysical work ; the top of the limestone was reached at a depth of nearly 4,000 feet, and proved to contain gas. In this well Stage I of the Lower Fars was found to be only two to three hundred feet thick, compared with 11,000 feet at Zeloi, 4 miles across the strike to the south-west ; the topmost beds of Stage I were strongly sheared, indicating that here, as in the N.W. part of Masjid-i-Sulaiman, the excessive reduction of this Stage is at least partly due to movement of the overburden across the limestone fold.

The geophysical method which is used for locating limestone domes is known as the Seismic Refraction Arc Method[1] (Jones, 1933). It has been found that the vibrations set up by an explosion are transmitted much more rapidly through a certain deep-seated medium (inferred to be the Middle Cretaceous Limestone-group) than through the overlying strata, and that if the recording seismometers are placed sufficiently far from the "shot-point" where the explosion takes place, they will receive the deep-seated vibration before the arrival of the much larger disturbance transmitted through the higher beds.

A number of seismometers are spaced out along the arc of a circle centred on the shot-point and 10–15 miles distant from it. A big charge of gelignite, usually 1–2 tons, is detonated at the shot-point, and the time of arrival of the deep-seated vibration at each seismometer is recorded. The several travel-times are corrected for differences of ground-elevation between the various seismometers, and are then compared. The greater the thickness of the overburden at the receiving end, the longer will the travel-time be; thus, if the arc straddles a limestone-anticline, the travel-times will be longer at the two ends than they are in the middle. In this way, by observing at a number of arcs spaced along the fold-trend, the axis of a limestone-fold can be traced with considerable precision; the fact that the high-velocity medium is probably the Middle Cretaceous limestone and not the Asmari limestone is of little consequence, since there is no appreciable structural disharmony between them. Once the axis has been traced the position of the culmination can be determined by the Line-Method, in which the seismometers are spaced out along a line passing through the shot-point; by this method it is also possible to calculate approximately the depth at which the limestone will lie.

The far-reaching disturbance of the Lower Fars presents a serious problem not only to the field-geologist but also to the exploitation-geologist, whose duty it is to watch over the progress of a drilling well and, above all, to ensure that it shall not enter the limestone, with its high-pressure fluids, without due warning. The natural difficulties are enhanced by the fact that coring is not generally employed, being too slow and too costly, so that only small fragments of rock are available for study. Fortunately, it so happens that in all the oil-fields discovered hitherto the basal member of the Lower Fars clings to the surface of the limestone and has not taken part in the disharmonic movements of the overlying beds. In the Iranian fields this basal member, known as the Cap-Rock, consists of 100–200 feet of massive anhydrite, enclosing one or more bands of foraminiferal limestone and, usually, a bituminous shale-band; the Cap-Rock is distinguished from other thick anhydrites in the Lower Fars not only by its detailed lithological succession, which shows little variation over wide areas, but also by certain special features of its texture, of the mineral inclusions it contains, and of the foraminiferal faunule in the principal limestone-band.

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[1] The Seismic Reflection Method, now more commonly employed elsewhere, has been found unsatisfactory in Lower Fars areas, probably owing to disturbed conditions.

The consistent presence of the Cap-Rock immediately above the limestone was pointed out by Professor Shand at Masjid-i-Sulaiman in 1919, but intensive microscopical study was not undertaken until 1923–24, when its special textural and faunal features came to be recognized. The excessive disturbance of the remainder of Stage I in that area prevented further progress being made, and even now the normal stratigraphical succession is very incompletely known there. In the Haft Kel field, on the other hand, the disturbance is less extreme, and considerable progress was made while the field was being delimited in 1927 and succeeding years; M. W. Strong carried out a remarkable detailed study of all the anhydrite-bands encountered in the wells, and succeeded in establishing a general zonal succession, based chiefly on the occurrence of different types of mineral inclusions.[1] As a result of this work it now became possible not only to recognize the Cap-Rock itself but also to tell when a well was approaching it, except in a few instances where the beds normally overlying it were cut out by faulting.

Concurrently with Strong's work at Haft Kel, intensive microscopical study of the Lower Fars limestone-bands was proceeding in the Iraq Petroleum Company's field at Kirkuk, where the limestones are much better developed, and the disturbance less severe, than at Haft Kel or Masjid-i-Sulaiman. It was found that many of the limestones preserved their individual peculiarities over long distances, and a large number of reliable key-beds were recognized. A correlation-scheme of the same kind was subsequently worked out in the Naft Khaneh—Naft-i-Shah field.

In the Gach Saran field in Iran, where development has been in progress since 1936, limestones are again well developed. The Lower Fars is greatly disturbed in this field, but the fortunate discovery of relatively undisturbed sections in the neighbouring country allowed the normal succession to be worked out in considerable detail. A comprehensive correlation-scheme, based on limestones and chemical inclusions, has been worked out, and it is now possible to recognize the presence of faults, overfolds, and overthrusts without much difficulty. Re-examination of the rock-samples from the first four wells, drilled in 1926–30, has revealed that the first of them penetrated a large overfold in the higher part of Stage I and passed back into younger beds, the second passed through a large overthrust and encountered a great part of the Stage twice over, the third found a nearly normal succession, and the fourth proved a defective one, with a considerable part of the Stage missing. The difficulty of dealing with such conditions, in the absence of rigorous stratigraphic control, may well be imagined.

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[1] An account of this stratigraphical method has been published by Strong (1937).

Much work on the above lines has since been carried out in other areas, both on the surface and in wells, and at Haft Kel the original correlation-scheme has been strengthened by the inclusion of a number of limestones which, though thin, have distinctive characteristics. At the surface much progress has been made with the elucidation of the Lower Fars structure in certain areas, though not yet with our understanding thereof.

In the foregoing pages we have tried to convey some idea of the history and characteristics of the great geological province in which the oil-fields of S.W. Iran and Iraq are situated. The feature which strikes one most forcibly is the grandeur of it all, the spaciousness of the geosyncline, the thickness of its sediments, and the noble scale and simplicity of the folding. Even the vexatious turbulence of the Lower Fars is, like a fault in a truly great man, also greatly conceived.

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CORRESPONDENCE

CORRELATION OF LAKI BEDS

Sir,—In a recent paper [1] discussing the distribution of early Eocene beds in North-West India, Mr. E. S. Pinfold has maintained (pp. 196–198) that the so-called "Dunghan Limestone" has no equivalent on the Punjab Salt Range; and since I was chiefly responsible for the stratigraphic conclusions expressed in our joint memoir [2] on the Eocene beds of that range, it may be supposed that I share this opinion. I therefore wish to say that I do not. I showed (*ibid.*, pp. 15, 32–33, etc.) that the entire Laki sequence on the Salt Range is older than the Shekhan Limestone of Kohat. Since, as I previously showed,[3] the Shekhan Limestone corresponds with the Upper Laki Limestone of Sind, it seems probable that the distinctly older Sakesar Limestone of the Salt Range correlates with the Meting Limestone of Sind, which Nuttall [4] regarded as equivalent to the "Dunghan Limestone" of Baluchistan. The still earlier Nammal Shales of the Salt Range display older characters than any other known Laki formation, and probably represent part of the elements whose absence further south is indicated by the Basal Laki Laterite of Sind.

With regard to the term "Dunghan Limestone", I think (as stated in a paper lately read before the Geological Society) that it would be less anomalous to call the formation in question the "Bolan Limestone". Nobody has ever figured Laki fossils from Dunghan Hill, or even shown that Laki beds exist there. The "Dunghan Limestone" fauna quoted by Pinfold in his present paper (p. 192) was described by Nuttall[1] from a limestone of Lower Laki age in the Bolan Pass; several of the species, and one genus, having never been seen elsewhere in India. Since Bolan fossils afford the actual basis for comparison when discussing this formation, I prefer to treat the Bolan as its type area in name, as it is in fact.

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[1] Pinfold, E. S., 1939. The Dunghan Limestone and the Cretaceous-Eocene unconformity in North-West India. *Rec. Geol. Surv. Ind.*, lxxiv, 189–198; pl. 12.

[2] Davies, L. M., and Pinfold, E. S., 1937. The Eocene Beds of the Punjab Salt Range. *Pal. Indica* (N.S.), xxiv.

[3] Davies, L. M., 1927. Supplement to "Notes on the Correlation of Pinfold's Chharat Series". *Trans. Min. Geol. Inst. Ind.*, xxi, 316–318, etc.

[4] Nuttall, W. L. F., 1925. The Stratigraphy of the Laki Series. *Quart. Journ. Geol. Soc. Lond.*, lxxxi, 417–453, pls. xxiii–xxvii.

I am glad to see that Mr. Pinfold endorses (p. 195) my statement[2] that the Laki is altogether missing in northern Waziristan. He thinks, however, that a small thickness of shales with an estuarine fauna of uppermost Laki age appears in southern Waziristan. I will not personally be sure of this until I have seen the fossils concerned, which have not yet even been specified. Reasons for caution in claiming Laki beds in Waziristan have been detailed elsewhere.[3]

Incidentally, I cannot agree with Mr. Pinfold's statement (p. 192) that "the whole of the Ranikot is missing" in Baluchistan. I long ago showed[4] that typical Upper Ranikot fossils had been collected at Zrind, in northern Baluchistan; and I recently found Ranikot foraminifera[5] in Carter's collections from the Valley of Kelat farther south. That Ranikot deposits are relatively rare in Baluchistan may be admitted; and this was probably due to local emergence and denudation during basal Laki times.

L. M. Davies.

PLATYCRINUS TUBERCULATUS OYENS, A CORRECTION

Sir,—On p. 300, vol. i, *Geological Expedition to the Lesser Sunda Islands under leadership of H. A. Brouwer*, Amsterdam, 1940, I described in my article "Neue permische Krinoiden, mit Angaben über deren Fundstellen im Basleo Gebiet (Niederländisch Timor)" a new species of *Platycrinus* under the name *Platycrinus tuberculatus*.

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[1] *Op. cit.*, pp. 420, 440, 448, etc.

[2] Davies, L. M., 1938. Eocene Beds in Waziristan. *Nature*, cxlii, 296.

[3] Davies, L. M., 1938. Quelques résultats de travaux récents sur l'Éocène du Nord-Ouest de l'Inde. *C.R. Soc. Géol. France*, Fasc. 2, 22–23. Quelques observations sur les derniers dépôts marins dans le Nord-Ouest de l'Inde. *Ibid.*, Fasc. 15, 294–295.

[4] Davies, L. M., 1927. The Ranikot Beds at Thal. *Quart. Journ. Geol. Soc. Lond.*, lxxxiii, 265.

[5] On British Museum (Nat. Hist.) slide No. P. 30214.

Mr. James Wright, of Edinburgh, was so kind as to call my attention to the fact that the name *tuberculatus* had already been used for a species of *Platycrinus* by J. S. Miller (1821), and that also Phillips (1836) and the Austins (1843–8) gave figures and descriptions of what they considered to be the same species.

Though recently Miller's species has been placed by Wright (1938) under *Pleurocrinus*, my species cannot stand under the name *tuberculatus* and consequently I propose to change *Platycrinus tuberculatus* Oyens, 1940, to *Platycrinus wrighti* nov. nom.

I am exceedingly indebted to Mr. Wright for calling my attention to this oversight.

F. A. H. W. de Marez Oyens.

Amsterdam, Geological Institute.
March, 1940.

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REVIEWS

The Birth and Development of the Geological Sciences. By F. D. Adams. pp. 506, with plates and figures. London: Baillière, Tindall and Cox, 1938. Price 22*s.* 6*d.*

In this charmingly written book Professor Adams has brought together the results of his own assiduous collecting and study of the early literature of geology, mineralogy, and allied subjects. It is generally believed that the actual word geology is very modern in its present sense, but it is here shown that it was actually used in English as early as 1661 and in Danish in 1657. But it is a curious point that the first known use of the word meant something entirely different. In 1473 Richard de Bury, Bishop of Durham, used it for, of all things in the world, the study of law, which he called the *earthly science* " in antithesis to the sciences which aid in the understanding of divine things ", namely theology.

All the same, geology is a very modern science. It is truly astonishing how long the old and fantastic ideas survived. The reference is here not so much to stratigraphical geology, which was badly handicapped by the necessity for conciliating Noah's flood, as to such matters as vulcanicity and the origin of ore-deposits, which really had nothing to do with the Mosaic cosmogony: in these reasonable progress might have been expected at a much earlier date: after all the Royal Society knew all about steam pressure in the reign of Charles II, but the notion of combustion in volcanoes lingered long after that. Mention may also be made of the strange connection between minerals and magic.

All of these points and innumerable others are set forth in the present book with a wealth of scholarship and an obvious enthusiasm which makes it probably the most readable of any history of geology that has yet appeared: the illustrations, nearly all reproductions of ancient engravings, are delightful.

THE PETROLOGY OF THE SKAERGAARD INTRUSION. By L. R. WAGER and W. A. DEER. *Meddelelser om Grønland.* Bd. 105, No. 4, pp. 352, with 27 plates, 68 figures, and a coloured map. Copenhagen: C. A. Reitzels Forlag, 1939. Price 20 Kr.

This lavishly produced and beautifully illustrated memoir presents the results of about a year's field work in 1935–6 on the great Skaergaard intrusion in the Kangerdlugssuaq Fiord, East Greenland, with a very complete laboratory investigation of the material collected. This intrusion, which covers about 50 km^2, is probably the best adapted of any known occurrence for the study of a layered complex, owing to its reasonable size and the very fresh condition of the Tertiary rocks. In simplest terms it is the product of the differentiation of a gabbro magma specially characterized by the crystallization of highly ferriferous olivine.

The general form of the intrusion is an inverted cone about 9,000 ft. high, somewhat tilted and deeply dissected. There is everywhere a narrow marginal facies without banding, but the main mass shows a most conspicuous layering. This is brought about by rhythmic variation in the proportion of light and dark minerals during differentiation: there is also a steady change in the composition of the solid solutions thus formed. Many of these crystals have a platy form and there is thus produced a kind of igneous lamination in each band. There is little difference in the silica percentage from bottom to top, but great variation in the iron and magnesia.

It is believed that at one time the intrusion consisted of a mass of crystals with about 20 per cent of interstitial magma, which together had the composition of the unlayered margin (an olivine-gabbro like the Porphyritic Central Magma of Mull). This underwent differentiation from below upwards with increasing iron and decreasing magnesia. Near the end there was enrichment in soda and potash felspars.

From various features the authors conclude that there have been flow movements within the magma, with a convection circulation. The rhythmic layering is explained by changes in the velocity of these convection currents.

It is impossible in the space here available to give any account of the ingenious methods by which the order of formation of the different layers has been worked out by study of the composition of the solid solution minerals composing them. This should be studied by all petrologists since the results here attained are particularly clear and convincing.

The trend of crystallization of the Skaergaard magma supports Fenner's view that during the crystallization of basalt there is absolute enrichment in iron. Comparison of analyses of Greenland and Mull basalts indicates that in the magma reservoirs from which they were derived differentiation was similar to that of the Skaergaard magma. The evidence of this magma shows that crystal fractionation leads to the formation of ferrogabbro and not to intermediate types of the calc-alkaline series. The rarity of ferrogabbros is taken to indicate that the bulk of post-Cambrian granites were not formed by fractional crystallization of basalt magma. This is an extremely important conclusion.

When we consider the conditions under which the field work was done and the immense amount of laboratory work involved we feel that the authors are to be heartily congratulated on what should eventually prove to be an epoch-making piece of work. It may be expected that the conclusions will eventually be extended to other and much larger banded complexes in different parts of the world.

R. H. R.

GEOLOGICAL MAGAZINE

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The Yorkshire Dogger

I. The Coastal Region

By R. H. RASTALL and J. E. HEMINGWAY

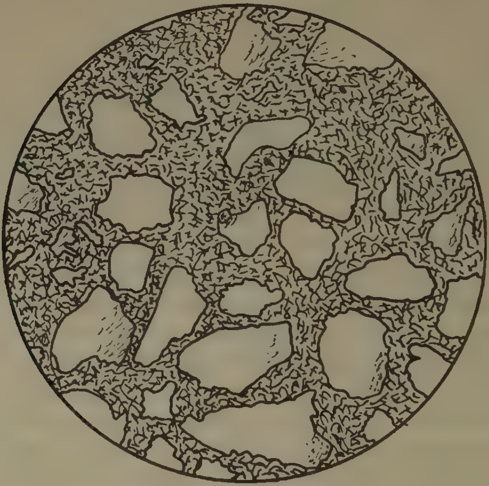
(*Concluded from p.* 197)

PETROGRAPHICAL DESCRIPTIONS

The Dogger of the coast from Peak to Kettleness is essentially a sideritic sandstone, and except in the Sandsend-Mulgrave district, is entirely unfossiliferous. This type of coast Dogger is well exposed at Hawsker Bottoms. To the naked eye it is a brownish sandstone of fine grain with very abundant white specks, a few small lenses of pale grey mudstone, and a very small number of bright green grains. Under the microscope it is seen to be a fairly well-graded sandstone with a few larger clastic elements, including both quartz and felspar as well as those mentioned above. The quartz grains are extraordinarily angular, doubtless due to corrosion by the matrix, and many of them are compound, i.e. microquartzites of various kinds. Felspar, mainly orthoclase and perthite, is abundant. A few flakes of chloritic chamosite and still more rare grains of typical speckled glauconite represent the green grains mentioned above. The matrix is somewhat oxidized, but still shows the usual well-formed rhombohedra of siderite, most of them with darker cores. The most notable point is that the sand grains rarely touch and are often widely spaced in the matrix, indicating simultaneous deposition of clastic elements and matrix, which is not a cement in the usual sense (Text-fig. 5). In this and in subsequent papers the term " cement " is used to connote that interstitial bonding material subsequently added to a bed of incoherent detrital grains which were lying in contact with each other before its infiltration : " matrix " is used for that interstitial material between detrital grains which are not in contact and which was therefore deposited contemporaneously with them, forming a part of the original sea floor deposit.

Within the Whitby Basin a number of minor variants of the typical sideritic sandstone are developed and are of considerable interest. Below Gnipe Howe, north-west of Hawsker Bottoms, the Dogger is to the naked eye a conspicuously banded rock, chiefly composed of speckled sandstone alternating with streaks of nearly pure dark grey mudstone, weathering red. In some bands there are a number of white ooliths, in others few or none.

In a thin slice the rock is wonderfully fresh. The speckled bands consist of sandstone with a siderite matrix. The grain size is extremely variable: some elements up to 1·5 mm. in diameter are very well rounded, but all the smaller ones are very angular and some of fantastic shapes. The grains are mainly quartz, a great many being microquartzitic. Felspars are common, chiefly orthoclase, often partly replaced by calcite, with rare fresh plagioclase. Some small roundish or angular bodies are also composed of calcite; these are probably the apparent ooliths of the hand-specimen. They are pebbles of limestone or perhaps shell fragments.



Text-fig. 5.—Sideritic sandstone showing typical dispersed distribution of sand grains in the matrix. × 36.

The matrix consists of very fresh pale granular siderite, without the usual dark cores. Here and there in the matrix are oval or somewhat elongated patches of a darker colour, almost brown, which at first sight suggest sideritized ooliths. However, a few of them enclose small quartz grains not at the centre, and at least one contains a kaolinitized oolith. They consist of darker siderite of finer grain than the matrix and there is no trace of concentric structure. Hence they are probably derived pebbles of siderite-mudstone.

A somewhat extreme variant of the Dogger of the Whitby Basin occurs in the derelict western bay of Peak Alum Works. Macroscopically this is a dark, very heavy and conspicuously oolitic sandy siderite rock, the ratio of the detrital elements to the matrix being very variable. In slices of average composition sand grains are not very abundant and are often widely spaced in the matrix. For the most part they are extremely angular and consist of quartz, quartzite, kaolinitized orthoclase, and perthite, some grains of felspar being fairly large, giving the characteristic speckled appearance to the hand specimen.

The most interesting feature of this rock is the white ooliths, which occur sporadically distributed in nearly all specimens of the coast Dogger though in strongly varying proportions: at one extreme is the oolitic siderite rock of Boulby in which white ooliths are almost the only macroscopic constituent (see p. 263), and at the other extreme speckled sandstones in which occasional ooliths can only be made out with difficulty. It may be emphasized that these white ooliths are clearly distinct from the green chamosite ooliths which occur abundantly within the Runswick lagoon and elsewhere in North-East Yorkshire.

The white ooliths are spherical or more commonly ellipsoidal bodies, nearly always battered and broken, corroded at the edges, never showing smooth outlines, being as a rule indented by the sharp siderite crystals of the matrix and sometimes partly replaced by siderite. They are composed of a colourless substance with a refractive index slightly higher than balsam, with extremely weak birefringence and sometimes apparently isotropic. This appears to depend a good deal on the size of the individual grains or flakes, the larger ones being naturally easier to see. In the study of these and other ooliths staining methods have been found extremely effective and have definitely proved that the white substance is kaolinite.

The technique of staining is very simple. An ordinary rock-slice, without coverslip, is immersed for a few hours in an extremely dilute solution of methylene blue in water. Chamosite turns to a deep greenish blue, while kaolinite becomes a delicate clear blue, with marked pleochroism, bright blue to nearly colourless, the stronger absorption being for light vibrating parallel to the thin edge of the flake, i.e. similar to coloured micas. The birefringence is peculiar and characteristic. It is very weak, while the dispersion is strong, so that the interference colours are quite abnormal, ranging from dull blue, through purple, crimson, and orange to yellowish green. Strong illumination and high magnification are necessary to see this effect satisfactorily, but when once seen it is unmistakable, and apparently structureless kaolinite can often be identified by this means in stained specimens.

Usually when thus stained it is easy to see the characteristic vermicular or rouleau structure of the kaolinite, which is often well developed, though some of the ooliths may still retain shreds and patches of very pale green chamosite, apparently little altered. The ooliths do not always show vermicular crystals: sometimes the kaolinite is so finely divided as to stain a uniform blue, then appearing to be isotropic or nearly so with crossed nicols and very commonly only part of the oolith consists of visible vermicular crystals. The ooliths frequently enclose a few rhombohedra of siderite. This character is more conspicuously developed in other localities, as at Boulby (Text-fig. 6).

From the above facts it is concluded that all the white ooliths occurring in the sideritic sandstones of the Whitby Basin, as well as the flakes and chips of more or less kaolinitized chamosite, are derived from some locality other than that in which they are found. Physically their corroded and battered appearance offers a striking contrast to the regular structure and smooth outlines of the ooliths of the chamosite-oolite facies of the Runswick Lagoon and elsewhere; mineralogically they are quite different, being kaolinitized and leached of their iron content. These white ooliths have doubtless been derived from the Runswick Lagoon where they were formed, being washed over the imperfect barrier of the Kettleness Ridge. Since these ooliths are enclosed in a perfectly fresh matrix of closely packed siderite, and even to some extent replaced by siderite, it follows that kaolinitization took place during transport or immediately upon deposition.

The matrix of the Dogger at Peak Alum Works consists of extremely fine-grained and perfectly fresh siderite of a pale brown colour, usually with a slightly paler shell round the ooliths and sand grains: this effect is not uncommon in the Dogger. In stained specimens high magnification shows a minute amount of interstitial chamosite and here and there are patches of disseminated pyrite. A few scraps of fossils are replaced by siderite rather darker in colour than the matrix.

Chips of the rock dissolved in 20 per cent HCl give only slight effervescence in the cold, but strong at a gentle heat, with much oily scum. The solution when filtered is of a clear green colour, showing that practically all the iron is in the ferrous state, which agrees with the fresh condition of the siderite matrix. The ooliths thus separated are pure white and on ignition become at the most extremely pale pink, the majority remaining perfectly white. This shows that kaolinitization is complete. The rest of the insoluble residue is a white sand with a very few flakes of muscovite. Owing to the low density of kaolinitized ooliths they may be easily panned off from the sand.

An unusual rock type occurs on the Scar at Whitby, near Yellow Sands, 500 yards east of the East Pier (see p. 185 for description of section). This is a pale grey, tough and fresh-looking rock with a few conspicuous pebbles up to 1 cm. in diameter and many smaller ones grading down to sand grains and with numerous bright green grains of glauconite. As tests showed the rock to be rich in carbonates large fragments were dissolved in dilute acid, only slightly warmed ; the residue was a fine gravel, mainly composed of quartz, felspar, and small pebbles, with not much fine sand. The solution when filtered was of the usual clear green colour, the filter retaining a good deal of oily black material of low density. In thin section the rock consists essentially of pebbles of quartz, felspar, phosphate rock, shell fragments, rounded pebbles of limestone (not ooliths), and sand grains, in a calcareous matrix. The larger grains up to 2 or 3 mm. are very well rounded, consisting of quartz and quartzite, but a large piece of microcline is sharply angular. The felspar grains also include some decomposed plagioclase. Many of the larger quartzes are surrounded by a thin shell of calcite and some appear to be partly replaced by calcite. This, however, may be replacement of felspar graphically intergrown with the quartz. Most of the small quartzes are extraordinarily angular.

The matrix consists of rhombohedra of fresh siderite of pale colour with the usual slightly darker cores, but there is also a small amount of interstitial calcite. It is clear that at the time of formation there was an unusually high concentration of calcium carbonate in the water, as is borne out by the presence of pebbles of limestone.

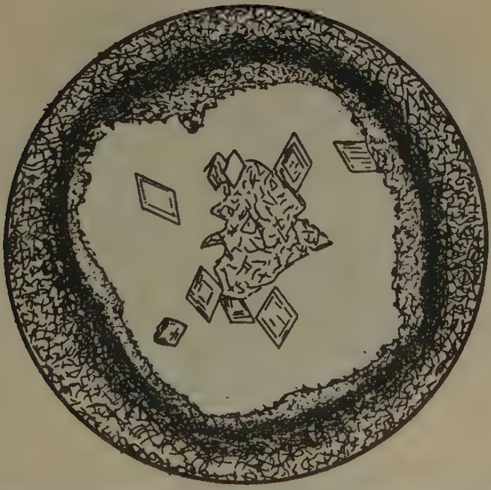
North-west of the Kettleness Ridge, within the Runswick lagoon, the facies changes completely, the Dogger being represented by oolites of various types, by chamositic sandstone and siderite-mudstone with only very subsidiary sideritic sandstones. A number of these lithological types will be described in detail.

The lower block from Cat Beck adit, Kettleness, immediately north-west of the Kettleness Ridge is macroscopically a pale blue, very pebbly oolite (Rastall and Hemingway, 1939*a*, p. 226). In the past this rock has been worked for ironstone. In thin slice it is mainly composed of nearly fresh chamosite ooliths in a matrix of siderite. The ooliths are rather large, spherical, or oval, with very sharp boundaries. They consist of pale yellowish green and very fresh chamosite, many showing good black crosses with crossed nicols. Their structure is markedly concentric, and a nucleus of flaky chamosite is often present. A few ooliths show slight kaolinitization in patches, with rouleau structure. The matrix consists of fresh siderite in large rhombohedral crystals, usually with darker cores. Accessory constituents of the rock include a few small phosphatized pebbles, many fragments of shells replaced by siderite and small lumps of kaolinitized chamosite-rock. Sand grains are not abundant, but are large and very angular, being mainly quartz and quartzite with some perthite felspar.

The upper block in the same section is obviously the same as specimens obtained in a much fresher condition from dumps near an old shaft ½ mile west-south-west of Kettleness Station. Macroscopically it is a purple-brown rock with conspicuous ooliths and angular rock chips of various pale colours, some even white. The matrix when fresh is blue grey and the rock may be described as a rather coarse oolitic grit. Thin sections show this to be a complex rock with no perceptible sorting, pebbles and sand grains of all grades being associated together. Many of the pebbles are pale grey cement-stone, while the sand grains are mainly quartz and quartzite, though variably kaolinitized felspar (orthoclase, microcline, and perthite) is common. Fragments of shells and wood are abundant and small grains of isotropic phosphatized rock are present.

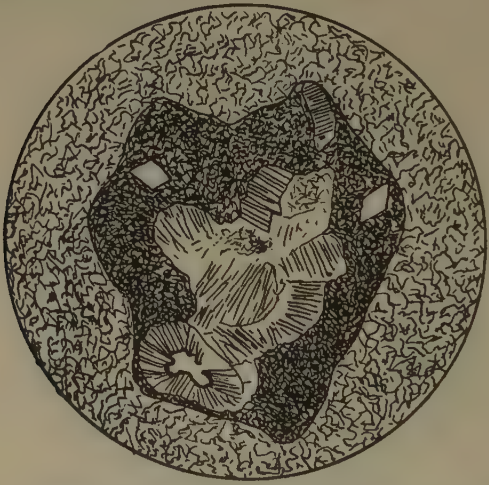
Ooliths are numerous, composed of pale green or pale brown chamosite with concentric structure. The kaolinitized ooliths may be derived but most appear to be primary. Some are indented by the matrix. There are also flakes of chloritic chamosite and small grains of kaolinite with rouleau structure, probably representing chamosite-mudstone. The conspicuous snow-white patches in the rock are composed of kaolinite: their origin is uncertain, though they may be derived from altered chamosite rocks. The matrix consists of nearly fresh siderite of variable grain size, from very coarse to fine, with a little disseminated sulphide.

An even finer example of oolite occurs in the cliffs above Port Mulgrave. After disintegration with very weak acid, the residue was mainly ooliths, with an exceedingly small proportion of sand. In slices the ooliths are estimated to form more than half of the rock. They are perfectly formed, round or oval and uniform in size, with well-marked concentric structure and perfectly sharp, smooth margins. They consist of very pale, greenish brown chamosite, with extremely low birefringence. About one in ten enclose a few rhombs of siderite arranged more or less concentrically near the margin, and a few are built up round a nucleus of siderite, an unusual feature. The matrix consists of almost perfectly fresh siderite, some almost colourless, of coarse grain and uniform texture. No shell fragments are present and the sand grains, which are few, are angular and subangular, of very variable size, and nearly all quartz. From their well-formed shape and the lack of corrosion or alteration it is considered that the ooliths are undoubtedly primary.



Text-fig. 6.—Boulby ironstone. Chamosite oolith in siderite. Oolith replaced by kaolinite (clear), with crystals of siderite and a scrap of green chamosite in centre. × 80.

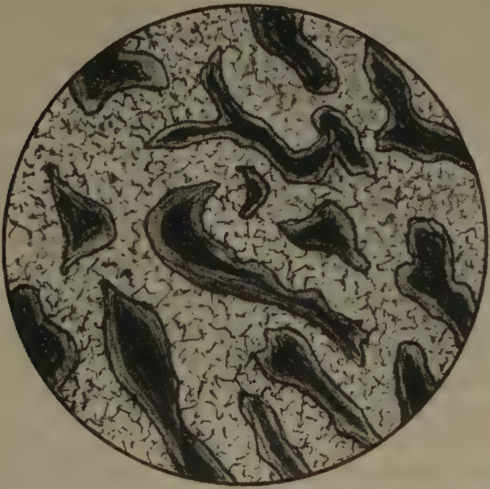
Another minor variation of the Dogger within the Runswick Lagoon may be seen in the ironstone once mined in Boulby Alum Works, which is entirely sand-free. It is a dense, dark grey, close-grained siderite rock with a very variable proportion of conspicuous white ooliths. In thin section the ooliths are small, round or more commonly oval, and composed of kaolinite. A fair number show flakes of very pale green chamosite as nuclei and nearly all enclose isolated and very perfectly formed rhombohedra of siderite in varying numbers, some being almost completely full of them (Text-fig. 6). Very rarely the vermicular structure of kaolinite may be seen without staining. On staining the siderite rhombs of the matrix may be seen to be held together by interstitial chamosite in small quantity. This is invisible in unstained slices.



Text-fig. 7.—Boulby ironstone. Lump of chamosite mudstone partly kaolinitized. × 80.

In Whitecliff Beck, Loftus, occurs perhaps the most remarkable rock seen in the whole course of our work. In the field section (p. 193) it is described as a greenish ironstone, and in the hand specimen it is in no way outstanding, being very dull, dark green in colour with an indistinctly spotted or streaky appearance, the streaks being more or less parallel to the bedding planes, rather like ill-developed foliation, as they are slightly wavy. In the unstained slice the rock is not distinctive, consisting mainly of pale green chămosite, in places full of crystals of siderite, with a few large irregular corroded quartz grains. The chamosite sometimes shows poorly defined ooliths with irregular outlines, but more commonly occurs as rather indefinite curly flakes. The less definite flakes are usually full of very small rhombohedra of siderite and are set in a matrix of siderite.

This extraordinary structure is brought out on staining with methylene blue and may best be understood with reference to the figure (Text-fig. 8). In it the darker portions represent the deeply stained cores : the margins are much paler (deep blue and green respectively with methylene blue), while the matrix is pale brown siderite. In these curious structures every gradation can be traced from nearly perfect ooliths, through various types with slight hooked ends to forms even more complicated than are shown in the figure. The staining also reveals the presence, as in many other instances of a small amount of interstitial chamosite between the siderite crystals of the matrix.



TEXT-FIG. 8.—Distorted ooliths (spastoliths) in chamosite-siderite rock, Loftus.

It is quite clear that these remarkable structures are essentially ooliths which have been pulled out of shape by disturbances of the sediment in which they were formed, by some sort of slumping, rolling, or current action. It therefore follows that they were originally deposited in a soft condition, probably as a gel. Similar structures have since been observed in many other chamosite-oolites all over the district. For them we propose the name of *spastoliths*, from the Greek *spastos*, pulled or drawn.

At Warsett Hill, Brotton, the Dogger varies much in character and is deeply weathered, but the outcrop is important in being the most northerly point at which the Dogger is represented. To illustrate its variability it may be noted that a hand specimen

4 × 2·5 inches shows the following types : (*a*) shelly ferruginous limestone with siderite matrix, (*b*) chamosite-oolite with siderite matrix, and (*c*) non-oolitic chamositic grit. Another more uniform specimen (sliced) is mainly a shelly chamosite-oolite with siderite matrix and a very high proportion of fossil fragments. Some of the ooliths are much oxidized chamosite, with a smaller number of calcareous ooliths.. Some rounded bodies (pseudo-ooliths) are really small pebbles of crystalline limestone. There is an average proportion of extremely angular sand grains but by far the greater part of the rock consists of calcareous shell fragments and other organic structures. Some are partly replaced by siderite and others, especially echinoderm spines, have their pores filled with oxidized siderite, but by far the greater part are wholly unaltered calcite. The latter point is of considerable significance in any consideration of the origin of these rocks. The matrix is mainly oxidized siderite, with here and there patches of altered chamosite and less commonly of calcite. This rock is the nearest approach seen on the coast to the chamositic limestones of the Bilsdale area and the western escarpment of North-East Yorkshire, which we hope to describe in detail later.

Within the lagoon chamositic sandstones occur in many localities. For the most part these are massive, well-graded rocks made up of subangular grains which average 0·25 mm. in length, though occasional larger and well-rounded grains are present. Chamosite ooliths occur only rarely in these rocks, as in the cliffs above Runswick, and altered, kaolinitized ooliths are entirely absent. The cement is chamosite, which partly replaces some of the quartz grains. Set in the chamosite cement, frequently in contact with the quartz grains, are abundant isolated siderite crystals averaging 0·04 mm. in length, some in the form of idiomorphic rhombs. Other siderite crystals are lightly in contact with each other and only rarely are they grouped into compact masses, though even in such cases the individual crystals are clearly distinct. Indeed a constant feature of the Dogger in all localities is the strong tendency for the siderite matrix or cement to form idiomorphic crystals. This is undoubtedly a recrystallization phenomenon occurring during the early stages of diagenesis of the rock.

For the most part the samples of chamositic sandstone examined were weathered. The siderite is heavily limonitized, partly masking the crystal form, while some of the chamosite is altered to kaolinite. These features are of only recent origin and are in no way related to the origin of the rock.

Many of the rocks of this series are rich in oily matter. Not only is the froth from acid treatment in nearly all cases very strong and dark in colour, leaving a thick oily residue on the vessels used, but many of them, when crushed, blacken readily on gentle heating in a closed tube, giving off a white vapour with a strong acrid smell and leaving oily drops in the tube. A considerable number also, when shaken with chloroform, give a notable reaction for oil. A very compact and quite ordinary sideritic sandstone from the corner of Stoupe Brow and Howdale is so oily that the crushed material, after passing the 30 mesh sieve, fails to sink in water and forms curious spheroidal globules. When shaken with chloroform this material gives a dark sherry colour. It has been noted that many preparations of separated fresh ooliths from the chamosite facies of the Dales blacken on ignition before turning red ; hence these also must contain some organic matter, probably as hydrocarbons (Rastall and Hemingway, 1939*a*).

CONSTITUENT MINERALS

Of that part of the light fraction which passes through the 30 mesh sieve the most common mineral is quartz ; much of this shows strain shadows and a large proportion, as seen in slices, consists of fine-textured quartzites of metamorphic origin. The marked angularity of most of the quartz is due to secondary corrosion in place by the matrix and in most specimens siderite crystals partly penetrate the quartz.

Felspar, either fresh or partly kaolinitized, is abundant, contributing largely to the speckled appearance of the rock. No pink felspar has been seen in hand specimens. All varieties of felspar occur, the most common being perthite and microcline ; orthoclase is common but plagioclase, especially basic types, is distinctly rare.

In the coast Dogger mica is not abundant unlike some associated inland facies and is not often seen in slices in any quantity.

Heavy mineral separations were prepared by solution of chips of rock in weak HCl, which obviated crushing and avoided the inclusion of minerals from the larger pebbles. For the most part the concentrates were well-graded and of fairly large size and consisted essentially of zircon, rutile, and tourmaline.

Zircon is the most abundant mineral and shows a great variety of types including purple and brown-zoned crystals. They are all well rounded.

Rutile is common, usually as broken or well-rounded grains, and shows an extraordinary range of colours : orange, red, crimson, brown, olive-brown, green, the purple-green pleochroic variety, sometimes twinned, and pale yellow, almost primrose colour, the last being very rare.

Tourmaline is rather scarce but also shows a great variety of colours; brown, blue, pink, olive-green, green zoned, pale yellow, prussian blue, and the pale varieties full of dusty inclusions.

Brookite is sporadically distributed, usually very rare except for the strange authigenic concentrate in the Black Oolite near Sandsend (Rastall and Hemingway, 1939). It is also abundant in rocks associated with the Black Oolite of Kettleness.

Anatase has not been observed except for a few obviously derived crystals with the brookite at Sandsend and Kettleness.

Chloritoid is present though in extremely small quantity in nearly all specimens as flakes with indigo-blue to olive-green pleochroism.

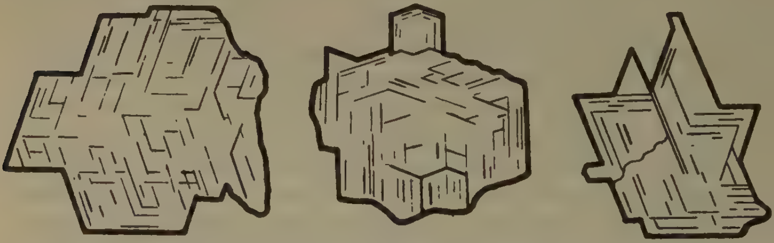
Monazite is present as small rounded grains, but is extremely rare.

Pyrite is variable, being dominant at Port Mulgrave. It occurs in aggregates of small crystals and as minute concretionary masses.

Green biotite and ilmenite are rare, though the latter is common near Whitby. Sphene has not been identified with certainty.

Garnet occurs in all sections but usually in minute quantities (see below). No other metamorphic minerals have been recognized, nor have pyroxene, amphibole, epidote, or fluorite.

The occurrence of garnet in the coastal Dogger is of great significance both genetically and stratigraphically. In a paper on the petrography of the Middle Jurassic sandstones of this area by the senior author the absence of garnet was pointed out as a distinctive characteristic of that series. Work on the heavy minerals of the Dogger of the coast proved the wide occurrence of this mineral in small quantities. It is of a peculiar type in the Whitby Basin where it is always colourless and nearly always possesses a well-defined dodecahedral cleavage, giving angles of 70° and 110°. It is present from Peak to Kettleness, being extremely rare and in very small grains in the east, increasing slowly both in quantity and size of grain westwards. A re-examination of the separations of Dogger east of the Peak Fault previously described has shown its rare occurrence in the upper 12 feet of the bed, without a trace below, showing that it was a late arrival. North-west of the Kettleness Ridge within the Runswick Lagoon colourless cleaved garnet rapidly



TEXT-FIG. 9.—Cleaved garnet, the Scar, Whitby. Note: the specimen was not crushed but separated by acid treatment.

increases both in abundance and size. Pink garnet also appears and increases similarly to the north-west. Both are large and very abundant at Boulby, and at Warsett Hill garnet of several types is the dominant heavy mineral.

With regard to the sand fraction as a whole, it is quite clear that much of it is derived either directly or indirectly from an area of igneous and metamorphic rocks. This is shown by the abundance of acid felspars and of sheared and mylonitized quartzites. The complete absence of amphiboles and pyroxenes from the heavy mineral suites suggests that this derivation is at least secondary and this is confirmed by the character of the zircons which are for the most part small and very well rounded. The extreme rarity of monazite and the very small size of the few grains found also tends to this conclusion, as this mineral is soft and will not resist long or repeated transport. There is no doubt that the brookite is authigenic and therefore throws no direct light on the origin of the sand. The problem of its origin has not been studied.

The discussion of the origin of the detrital constituents of the coast Dogger will be deferred to a later paper, when the evidence from the whole of North-East Yorkshire will be considered. It may, however, be stated at this point that there is strong evidence for their derivation in the main if not entirely from the Millstone Grit of the Pennine area.

SEA-FLOOR REACTIONS

The theory that ironstones were originally limestones that had undergone metasomatic change, the calcium carbonate being replaced by iron carbonate, was originally advanced by Sorby and was generally supported for almost seventy years (Sorby, 1856). This was finally disproved by Hallimond, who conclusively demonstrated that British bedded ironstones are essentially aqueous, usually marine, chemical precipitates (Hallimond, 1925). It is interesting to note that Sorby found support for his theory in the analysis of a shell " from the inferior oolite of Robin Hood's Bay ", 75 per cent of which was made up of iron carbonate. Doubtless this was the well known *Nerinaea* bed of Blea Wyke Point, a lenticular sideritized shell-bank occurring in the Dogger on the east side of the Peak Fault (Rastall and Hemingway, 1939*b*).

The examination of the Dogger, both of the coast and elsewhere, strongly supports the view that it is primarily an unaltered sedimentary rock which has undergone no profound metasomatism. That it is a marine deposit is undoubted, for at Mulgrave and Sandsend it yields an abundant marine fauna, usually specially rich in *Terebratula.* It is true that sideritization of some of the constituents of the Dogger has taken place. Shell chips in the Dogger of the Runswick Lagoon as well as the fossils of the *Nerinaea* bed are completely replaced by siderite, while many of the nuclei of the derived white ooliths are replaced by siderite rhombs. This, however, in no way invalidates the main argument, for the effect was only local. In such localities as Sandsend and Brotton unaltered calcite shells occur in a siderite matrix, conclusively demonstrating that the Dogger did not originate from the replacement of a limestone.

The Dogger of the Whitby Basin is a sideritic sandstone of a special type. In the majority of specimens examined the sand grains do not touch and they are often widely separated. Indeed small lenses and bands of almost pure siderite occur and there is every gradation from this extreme to rocks composed mainly of sand with merely interstitial siderite. Hence it is clear that siderite is a not a subsequent cement, but that all constituents of the rock were deposited at the same time. The white ooliths are derived and are for all purposes equivalent to sand grains

From the structure of the rock, particularly the distribution of the sand grains, it is clear that at the time of deposition the detrital material was supported in a siderite matrix which was sufficiently strong, though still incoherent, to prevent the sinking of the sand grains. In other words the siderite was doubtless deposited in a finely crystalline form analogous to the aragonite mud which is precipitated on the Great Bahama Banks (Black, 1933), but in which detrital material was interspersed. At a later stage, during consolidation, the siderite recrystallized to a coarser well-shaped rhombohedral form in which it is now found.

Within the Runswick Lagoon sea-floor reactions were more complex and the resulting rocks were still more varied because of the irregular distribution of detrital material. In favoured localities as at Port Mulgrave fairly pure chamosite-oolites with a siderite matrix were formed. The occurrence of these two minerals together is not incompatible with their origin as primary sea-floor deposits for, as Hallimond has pointed out, the formation of chamosite and siderite are independent reactions which may proceed side by side. This deposition was accompanied by sufficient agitation to prevent the immediate welding together of the minerals to form chamosite-siderite mudstones, and resulted in the concentric deposition of chamosite, usually round chamosite nuclei.

From such a locality as this fresh chamosite ooliths were washed into more sandy areas within the lagoon where they contributed to the formation of sandy chamosite-oolites. Others were carried over the Kettleness Ridge and were sparsely distributed throughout the sideritic sandstones accumulating outside the lagoon. During this transport they were altered both physically and chemically to white battered kaolinite ooliths. It is significant that within the lagoon white ooliths are found most abundantly at Boulby. A few occur in the ironstone mined near the Kettleness ridge but over the rest of the lagoon they are virtually absent. It would therefore appear that those chamosite ooliths which were carried by wave action into the shallowest waters of the lagoon particularly bordering the northerly shore near Boulby were leached of their iron content, possibly by higher CO_2 content of the water, the chamosite " skins " being replaced by kaolinite and the nuclei by siderite.

At other localities within the lagoon, such as Limekiln Beck, sandstones were deposited with a cement that was chiefly chamosite, with only subsidiary siderite. The complete absence of ooliths in many of these rocks, either as detritus or as primary deposits suggests that they were laid down in relatively deeper areas of the lagoon, in " dead water " below the limit of constant gentle agitation and consequent oolite formation.

THE PEBBLES

As will be seen from the descriptions of sections, pebbles occur very frequently in the Dogger. Usually they are concentrated in the base of the bed, not as a separate bed, as earlier authors suggest, but forming an integral part of the main block. They decrease upwards both in number and size, but may occur as a second or even a third layer at higher levels, frequently resting upon the upper surface of one of the massive beds. In exceptional cases, as at Overdale, near Sandsend, they form conspicuous beds up to a foot or more in thickness.

In size the pebbles range from the smallest grains up to 3 inches in length, averaging ¾ inch. They vary in shape from almost perfect spheres to highly irregular forms, while some show the well-worn flattened ovoid form of typical beach pebbles.

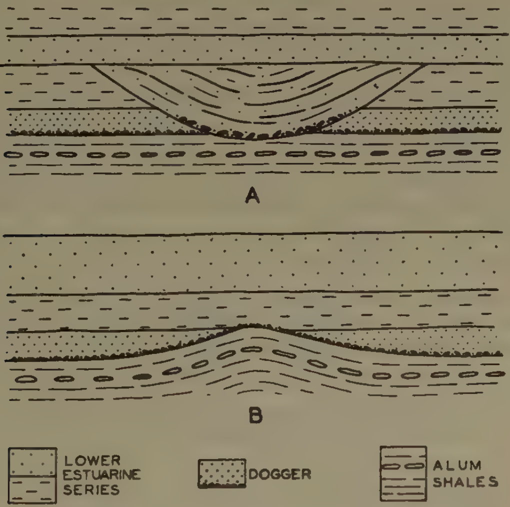
In earlier papers on the Dogger much space is devoted to the question of whether these bodies are pebbles or concretions.

The difficulty may have arisen from the fact that they are all of fine-grained rocks which in the then elementary state of sedimentary petrology could not be identified, and also, in part, from a looseness of terminology. It may be said at once that they are true pebbles and that no authigenic concretion has ever been found. Fragments of the characteristic pale grey cement-stone from nodules in the upper part of the Upper Lias are most abundant, as well as mudstones of various colours. These Whitbian and Yeovilian nodules are undoubtedly of concretionary origin, but waterworn fragments derived from them and subsequently incorporated in the Dogger are true pebbles of allogenic origin.

Fossil fragments, usually worn pieces of the outer whorls of ammonites, are of frequent occurrence, though rather sporadically distributed. The majority of these are most probably *Grammoceras striatulum*, with *Dactylioceras* and *Hildoceras* in decreasing abundance. While accurate identification of worn fragments is clearly impossible, it may be emphatically stated that no Lower Lias forms have been found as was originally claimed (Barrow, 1888). There is indeed no evidence from the derived fauna of this region of pre-Dogger erosion below the Alum Shales of the Whitbian. More rarely other fossils also occur, usually worn lamellibranchs or a coral fragment, probably *Thecosmilia*. All these are undoubtedly derived, being with the nodules the only materials sufficiently hard to resist erosion successfully. Occasional wood fragments also may be found.

Less abundant and usually smaller are pebbles of oolite, sometimes with a black matrix. The ooliths are sometimes chamosite only slightly leached, but more often they are completely kaolinitized and show every indication of being so altered before inclusion in the matrix. This matrix, brown in transmitted light, is isotropic and like the mudstone pebbles is phosphatic. Some dozens of pebbles were tested chemically and all gave a positive reaction to the phosphate test. Pebbles of a greenish fine-grained and well-graded sericitic sandstone are still rarer. These contain occasional ooliths and like the other types the matrix is now phosphatized, a change brought about while the pebbles were lying on the sea-floor. The distribution of each of the three types of pebbles, excluding the rolled fossil fragments, is variable. On the average the fine-grained sandstone totals 5 per cent; the phosphatized oolite 15 per cent; and the phosphatized mudstone 80 per cent.

The origin of the former two types of pebbles is in doubt. There are no far-derived pebbles in the Dogger and it is unlikely that these have been transported far. The oolites are unlike the chamosite-oolites of the Middle Lias even if erosion has gone so deep, which is improbable. While it is possible that they are relics of Yeovilian strata which once extended over this area the close similarity of the pebbles to existing Dogger sediments cannot be overlooked. It is not unlikely that erosion and sedimentation were both actively proceeding in the region at the same time and that these pebbles are the products of contemporaneous erosion.



Text-fig. 10.—“ Wants ” in the Dogger.

A. Washout type—absence of Dogger due to subsequent erosion by Lower Estuarine washout.

B. Barrier type—absence of Dogger due to non-deposition.

Summary of Conclusions

The Dogger of the Yorkshire coast (mainly Lower Aalenian) rests non-sequentially upon Alum Shales (Whitbian). Marine Upper Aalenian deposits (*murchisonae* beds) have been definitely recognized only in the north-west, though representatives may occur in other localities.

The Dogger is marine throughout, laid down in fairly shallow water on a surface thrown into low folds at the end of Yeovilian times. Two principal facies variations are recognized :

(*a*) sideritic sandstone occurring from Peak to Kettleness and laid down in fairly open water (the Whitby Basin); (*b*) non-oolitic chamositic sandstones with little or no siderite and primary chamosite-oolites with a siderite matrix. The latter occur from Kettleness to Boulby and were deposited within the Runswick Lagoon, about six miles wide. The two facies were separated by a submarine shoal or barrier at Kettleness and the position of the shore of the lagoon is also located.

The relation of the clastic elements to matrix in the sandstones shows that the matrix was deposited contemporaneously with the clastic elements.

Although in some localities calcareous shells are replaced by siderite, more commonly shells and fragments of limestone embedded in the siderite matrix are unaltered. The siderite is primary and not a replacement of calcite.

In the sideritic sandstone facies as developed between Peak and Kettleness all ooliths are derived. These are always more or less kaolinitized and the nature of the kaolinite has been established beyond doubt by staining methods.

Within the Runswick Lagoon chamosite, usually as ooliths, and siderite were deposited simultaneously.

In this type of rock chamosite ooliths sometimes show so much distortion that although now consisting of normal crystalline chamosite, they must have been deposited in a soft condition, probably as a gel.

Among the heavy minerals colourless cleaved garnet is found in all localities, being very rare in the east, increasing westwards. Within the Runswick lagoon red garnet occurs and in the extreme north-west garnet of both types is dominant in heavy mineral concentrates, suggesting derivation from the west or north-west.

Besides the usual phosphatized mudstones, the pebble beds nearly everywhere contain many pebbles of oolites with a black matrix and less commonly fine-grained sandstones, all phosphatized. The source rocks of these pebbles are not known in situ.

More or less siliceous iron silicate-carbonate rocks, such as might give rise to the " banded ironstones " of the Precambrian, have been formed by normal marine deposition and sea-floor reactions.

Finally we wish to express our thanks to Mr. K. O. Rickson, of the Department of Mineralogy and Petrology, Cambridge, for drawing some of the diagrams, and to Mr. C. E. Drake

of the same department for his care and skill in cutting microscope sections of these soft and difficult rocks, and for the interest that he has shown in helping us to get good results from some rather unpromising material.

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Foraminifera in Boulder Clays from the Wexford Coast of Ireland

(With a note on the generic name *Streblus* Fischer)

By W. A. Macfadyen

FOUR samples were sent to me by Mr. A. Farrington, two pairs collected from separate boulder clays, in each of two localities. The purpose was to investigate whether it would be possible to differentiate the two clays by their respective content of microfossils.

Mr. Farrington writes (*in lit.*) that he has no doubt that there is a considerable age difference between the two boulder clays. The line of separation is sharply marked, and the lower bed exhibits evidence of pressure and kneading that is not visible in the upper bed. This is clear when the two beds are exposed together; but frequently only one is exposed and the ascription of such an exposure to a particular bed on physical evidence alone is too uncertain. It is here that the Foraminifera would be of such value if they showed anything definite.

The samples, as follows, were collected from the Townlands of Clones Middle, and Clones Lower, on the coast of North Wexford, about a mile south of Kilmichael point, the most prominent headland between Arklow and Courtown.[1]

A. Upper Boulder Clay, Clones Middle: "2 feet above junction with lower clay." 12½ oz. of dry clay yielded 3 oz. of washed residue, = 24 per cent; Foraminifera frequent.

B. Upper Boulder Clay, Clones Lower: "6 inches above junction with lower clay; clay jointed but plastic; rootlets." 6¾ oz. of dry clay yielded ½ oz. of washed residue, = 7·4 per cent; Foraminifera frequent.

C. Lower Boulder Clay, Clones Middle: "Two feet above platform of 'preglacial' raised beach; stony boulder clay." 10½ oz. of dry clay yielded 5¼ oz. of washed residue, = 50 per cent; Foraminifera few.

D. Lower Boulder Clay, Clones Lower: "2 feet above platform of 'preglacial' raised beach; much compressed and kneaded, dry." 10 oz. of dry clay yielded 2½ oz. of washed residue, = 25 per cent; many Foraminifera.

In the event, the size of the samples proved insufficient for a reasonably complete fauna to be recorded, owing to the relative sparsity of the Foraminifera. Larger samples, of about 2 lb. each, would almost certainly give richer and probably more consistent results.

The Foraminifera were almost all very small in size; after sieving to remove pebbles and grit, they were floated out of the washed residue by carbon tetrachloride. This method yields a very small concentrate consisting mainly of Foraminifera.

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[1] A. Farrington, 1939. Glacial Geology of South-Eastern Ireland. *Proc. Geol. Assoc.*, l, 337–344.

This small investigation shows that, on the basis of the four samples examined, there seems to be little hope of distinguishing the two different boulder clays by their content of microfossils. The common species are common to both clays, and both contain the same small fauna of derived Upper Cretaceous (Chalk) Foraminifera. The rare species, one or two specimens only being found in a sample, are wholly unsatisfactory characteristics; they are easily overlooked, and larger samples would probably often show that a species was not, in fact, confined to one of the two clays.

Points of interest in the results are, firstly, the indication of a climate colder than that of the present day Irish coast. This is shown by the presence of *Nonion orbicularis*, *Globigerina pachyderma*, and *Eponides frigidus*, all three forms being typically arctic in their habitat, though occasional specimens of them are recorded from the west coast of Scotland and even farther south. The *common* occurrence of *Nonion orbicularis* is therefore of most significance here.

Secondly, the Foraminifera recorded are purely marine in habitat, and not brackish water forms. This is shown particularly by the presence of *Elphidium crispum*, *Globigerina bulloides*, *Uvigerina* spp., *Cassidulina* spp., which do not tolerate brackish conditions. The absence or rarity of forms typically abundant in brackish water deposits agrees with this conclusion. Such forms are *Quinqueloculina fusca* Brady, *Trochammina* spp., *Streblus beccarii* (Linné), *Nonion depressulus* (Walker and Jacob), *Elphidium incertum* (Williamson), and *E. excavatum* (Terquem). However, it is just possible that the absence or rarity of at least some of these, such as *Streblus beccarii*, *Quinqueloculina fusca*, and *Trochammina* spp., might be ascribed to the colder climate.

The Foraminifera derived from the Upper Cretaceous may have come either directly from outcrops of the Chalk, or secondarily from a deposit itself containing derived Chalk Foraminifera. It is significant that almost all these derived Chalk forms are minute species easily transported in sea water, the larger forms not being found.

Comparison with Joseph Wright's lists in "The Post-Tertiary Foraminifera of the North-East of Ireland"[1] shows that the present results are not dissimilar as regards his boulder clays. He lists from them a total of sixty species from twelve samples, individual samples containing from three to fifty species, with an average of nineteen. Differences in the modern and older nomenclatures make comparisons difficult for the non-specialist, so that the following equivalents may be noted.

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[1] J. Wright, 1886. *Proc. Belfast Nat. Field Club*, i, Appendix V, 149–163.

Modern Names.		*Wright's Names.*
Buliminella elegantissima (d'Orbigny)	=	*Bulimina elegantissima* d'Orb.
Bolivina variabilis (Williamson)	=	*Textularia variabilis* Will.
Bolivina pseudoplicata Heron-Allen and Earland	=	*Bolivina plicata* d'Orbigny
Uvigerina peregrina Cushman	=	*U. pygmaea* d'Orbigny
Discorbis	=	*Discorbina*
Eponides frigidus (Cushman)	=	*Pulvinulina Karsteni* (Reuss)
Cibicides	=	*Truncatulina*
Streblus beccarii (Linné)	=	*Rotalia beccarii* (Linné)
Nonion	=	*Nonionina*
Elphidium	=	*Polystomella*
Elphidium incertum (Williamson)	=	*Polystomella striato-punctata* (Fichtel and Moll), *partim*

The record of microfossils found in the four samples is as follows :—

Pleistocene Foraminifera, etc.	A	B	C	D
	Upper Clay		*Lower Clay*	
Quinqueloculina sp. indet.	I	I	—	V
Textularia gramen d'Orbigny	I	—	—	—
Bulimina affinis d'Orbigny	—	—	I	I
,, *marginata* d'Orbigny	I	I	—	I
,, *pupoides* d'Orbigny	I	I	I	V
Buliminella elegantissima (d'Orbigny)	—	—	—	I
Virgulina schreibersiana Czjzek ?	—	—	—	I
Bolivina alata (Seguenza)	—	I	—	—
,, *pseudoplicata* Heron-Allen and Earland	X	V	V	X
,, *spathulata* (Williamson)	I	I	I	—
,, *variabilis* (Williamson)	—	—	—	I
,, *tortuosa* Brady	I	—	—	—
Cassidulina crassa d'Orbigny	X	X	X	X
,, *laevigata* d'Orbigny	—	I	—	V
,, *subglobosa* Brady	—	I	—	—
Lagena biancae (Seguenza)	—	I	—	I
,, *catenulata* (Jeffreys MS., Williamson)	—	—	—	I
,, *lineata* (Williamson)	—	—	—	I
,, *marginata* (Walker and Boys)	—	—	—	I
,, *orbignyana* (Seguenza)	I	I	—	I
,, *semistriata* Williamson	—	I	—	—
,, cf. *acuticosta* Reuss	I	—	—	—
Cristellaria acutauricularis (Fichtel and Moll)	—	—	—	I
,, *crepidula* (Fichtel and Moll)	I	I	—	—
Uvigerina angulosa Williamson	X	V	I	X
,, *peregrina* Cushman	I	—	—	—
Globigerina bulloides d'Orbigny	X	X	V	X
,, *pachyderma* (Ehrenberg)	I	—	—	—
Discorbis chasteri (Heron-Allen and Earland)	—	—	—	I
,, *globularis* (d'Orbigny)	—	—	—	I
,, *obtusus* (d'Orbigny)	—	I	—	I
,, *valvulata* (d'Orbigny) ?	—	—	—	I
Eponides frigidus (Cushman)	—	—	—	I
Cibicides lobatulus (Walker and Jacob)	X	V	V	V
,, *refulgens* Montfort	I	I	—	—

Pleistocene Foraminifera, etc.	A	B	C	D
	Upper Clay		*Lower Clay*	
Anomalina ammonoides (Reuss)	I	—	—	—
Streblus beccarii (Linné)	I	I	I	—
Nonion orbicularis (Brady)	X	V	X	X
„ *pauperatus* (Balkwill and Wright)	—	I	—	—
„ *depressulus* (Walker and Jacob) ? [1]	X	X	X	X
„ sp. indet.	—	—	I	—
Elphidium crispum (Linné)	—	—	—	I
„ *incertum* (Williamson)	V	I	I	I
„ *macellum* (Fichtel and Moll)	I	I	I	—
Total species 44	23	24	14	28
Ostracods (unidentified)	I	I	—	—
Foraminifera, etc., derived from the Upper Cretaceous				
Eouvigerina serrata (Chapman)	I	—	—	I
Gümbelina globulosa (Ehrenberg)	I	I	—	I
Globigerina aspera (Ehrenberg)	I	I	I	I
„ *cretacea* d'Orbigny	—	—	—	I
Anomalina lorneiana (d'Orbigny)	I	I	—	—
Gyroidina nitida (Reuss)	—	I	I	I
Chalk spheres	I	V	I	I
Total species 7	5	5	3	6

Note.—I = very rare (1–4 specimens found) ; V = rare (5–9 specimens); X = frequent (10 specimens or more).

NONION ORBICULARIS (Brady) and *N. DEPRESSULUS* (Walker and Jacob)

The arctic *N. orbicularis* may differ from the more widespread *N. depressulus* in the aperture, which sometimes has a row of pores instead of a narrow slit at the base of the final chamber, and most conspicuously in the greater inflation of the test.

Both forms may have from seven to twelve visible chambers, but in the material available I find that specimens having about eight chambers are far the commonest in each species.

In such papers of his as I have noted, Joseph Wright has not recorded *N. orbicularis*, though he frequently had *N. depressulus* in quantity. To investigate the discrimination of the two species a number of specimens (including topotype material of one of them), and published figures of both, were measured to compare the ratio of thickness to diameter of the test, the clearest distinction between them. The specimens on three of Wright's Boulder Clay slides (now preserved in the Mellard Reade Collection in the Sedgwick Museum, Cambridge), were also included in the examination, which yielded the following results :—

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[1] These specimens are small, rather variable, and not quite typical, commonly having a small umbilical boss ; they may provisionally be referred to *N. depressulus*.

N. orbicularis.	*Ratio of maximum thickness (taken as unity) to diameter of test.*
Brady's type figure (1881, *Ann. Mag. Nat. Hist.*, (5), viii, pl. xxi, fig. 5)	1·50
Figure by Madsen (1895, *Medd. Dansk Geol. Foren.*, No. 2, plate, fig. 7)	1·75
Figure by Cushman (1930, *U.S. Nat. Mus., Bull. 104*, pt. 7, pl. v, fig. 2)	1·79
Figure by Macfadyen (1932, *Geol. Mag.*, pl. xxxiv, fig. 14)	1·81
Ten specimens taken at random from the present material, four samples of Boulder Clays from Wexford (Text-fig. 1 below, 1·76)	1·59–1·93, mean, 1·75
N. depressulus.	
Two specimens, sub-Recent Clay, Cuckmere Haven, Seaford, Sussex	mean, 2·16
Two specimens, Recent shore sand, Sandwich, Kent	,, 2·23
Two specimens, Recent shore sand, Dunkerque, N. France	,, 2·26
Three specimens, sub-Recent Roddon silt, March, Cambridgeshire	,, 2·27
Three specimens, Holocene clay, Udalain, Isle of Skye	,, 2·31
Ten specimens, Recent shore sand, Reculver, Kent (Topotype); 2·15–2·58 (Text-fig. 2 below, 2·31)	,, 2·32
Three specimens, Holocene clay, Island Magee, Antrim	,, 2·41
Two specimens, sub-Recent clay, Romney Marsh, Kent	,, 2·44
Two specimens, sub-Recent clay, Borth, Cardiganshire	,, 2·57
Figure by Heron-Allen and Earland (1916, *Trans. Linn. Soc. Zool.*, xi, pl. xliii, fig. 7)	2·73
One specimen, Recent shore sand, Dunkerque, N. France (exceptional)	3·30

From these measurements it may be concluded that the ratio of thickness (taken as unity) to diameter in *N. orbicularis* varies from about 1·50 to 1·93, whereas in *N. depressulus* it varies from about 2·15 to 2·73, exceptionally to over 3·0. The dividing line between the two forms seems thus to lie about 2·0.

Joseph Wright's Specimens [1]	
Eight specimens, Boulder Clay, Seacombe, Cheshire (Sedgwick Mus. slide No. 620)	1·70–2·88
Eight specimens, Boulder Clay, Great Crosby, near Liverpool (Sedgwick Mus. slide No. 619)	1·54–2·54
Four specimens, Boulder Clay, Clonakilty, Co. Cork (Sedgwick Mus. slide No. 622)	1·67–2·50

Thus it appears that while most of Wright's specimens on these three slides fall into *N. depressulus*, yet there are some which must be regarded as *N. orbicularis*. It is suggested that in cold climatic conditions, *N. depressulus* tends to develop a considerably more inflated test, sometimes with an aperture of a row of pores instead of the usual slit. Such specimens have been recorded as a distinct species with the name *N. orbicularis*, though they might, perhaps, better be regarded merely as a variety of *N. depressulus*.

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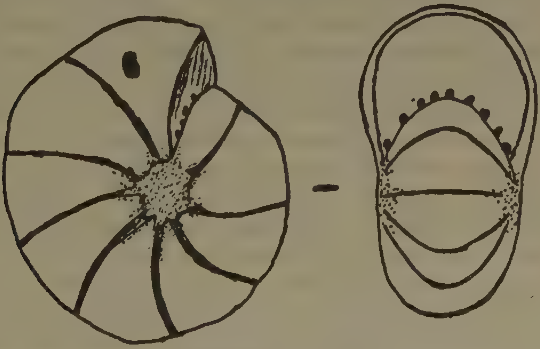
[1] Note that thick specimens were specially sought among the large number on the slides.

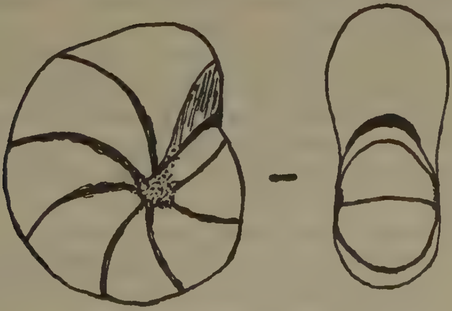
The very thick specimen that is now figured (Text-fig. 1) is this extreme form, while a topotype specimen of *N. depressulus* is figured for comparison (Text-fig. 2).



TEXT-FIG. 1. × 100

Nonion orbicularis (Brady)

Lower Boulder Clay, Clones Lower, Wexford. (Sedgwick Museum Slide No. 670)



TEXT-FIG. 2. × 100

Nonion depressulus (Walker and Jacob)

Topotype specimen, Recent shore sand, Reculver, Kent. (Sedgwick Museum Slide No. 671)

THE GENUS *STREBLUS* FISCHER, 1817

This generic name seems never to have been taken into use by later authors, the only species assigned to it by Fischer[1] (*Nautilus beccarii* Linné) having been included in the genus *Rotalia*.

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[1] G. Fischer de Waldheim, 1817. *Mém. Soc. Imp. Nat. Moscou*, v, 449.

The genotype of *Rotalia* Lamarck is *R. trochidiformis* Lamarck, which, as Colonel L. Merson Davies has shown[1] is most probably not congeneric with "*Rotalia*" *beccarii*. A separate generic name is therefore required for this species, and *Streblus* appears to be the earliest available name, antedating another possibility, *Turbinulina* d'Orbigny, 1826.

In his description of *Streblus* Fischer designated no type, but as the only specific name mentioned in his description and synonymy is *Nautilus beccarii* Linné, that species automatically becomes the monotypic genotype.

Fischer, writing in Latin, begins: "Streblus (a *στρεβλος*, tortuosus Tab. xiii, f. 5. a. magnitudine naturali; b. aucta) . . .", and then continues with his description of the generic characters. The word "tortuosus" is merely given as the translation of the Greek word which is the origin of the generic name[2]; it is not a trivial name at all. However, it misled d'Orbigny, who in his 1826 memoir[3] lists under Genus VI, *Rotalia* Lam., iv, sub-genus *Turbinulina* d'Orb., no. 40, *T. tortuosa* Fischer d'Orb., and made his Modèle No. 74 of it, according to Sherborn.[4] This must have been taken from Fischer's only figure, No. 5, which d'Orbigny assigned to the mythical *S. tortuosus*. Sherborn, in his Index (under *Streblus*), followed d'Orbigny, though he recognized that Fischer was dealing only with Linné's species *Nautilus beccarii* (footnote, p. 380).

In his synonymy Fischer refers to *N. beccarii* Linné, Gmelin, p. 3370, n. 4, and to figures by Martini and Gualtieri. On checking, these seem both to represent *S. beccarii*, and both are quoted by Linné in his synonymy. Fischer's own figure of *Streblus*, given without a specific name, is perhaps copied from Martini's figure 178.

There is, therefore, no doubt that Fischer is concerned only with Linné's species *N. beccarii*. To clinch the matter, and to show that he is not erecting a new species, he writes of *Streblus*, "*Auctores perplures cognoverunt testam istam pulcherrimam.*"

It may be added that Fischer's later description[5] and figure of *Streblus* are exact reprints of those of 1817.

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[1] L. M. Davies, 1932. *Trans. Roy. Soc. Edin.*, lvii, 408.

[2] Such translation is Fischer's regular habit in recording most of his genera.

[3] A. D. d'Orbigny, 1826. *Ann. Sci. Nat.*, Paris, vii, 275.

[4] C. D. Sherborn, 1893–6. An Index to the Genera and Species of the Foraminifera. *Smithsonian Misc. Coll.*, Nos. 856 and 1031; footnote, p. 380.

[5] G. Fischer de Waldheim, 1819. *Adversaria Zoologica*, fas. ii, 4to. Moscow, p. 75, pl. iii, fig. 5. This is a separate publication which reprinted the article from the periodical.

Graptogonophores

By G. L. Elles, Sedgwick Museum, Cambridge

THE sac-like structures occasionally found in association with graptolite rhabdosomes have always attracted the attention of palaeontologists whenever recognized. They have very generally been regarded as of reproductive character, though in some cases doubt has been held as to whether they were really attached to the rhabdosome; any specimens showing attachment beyond the possibility of doubt are therefore valuable, and in the case of the specimens now figured this attachment is particularly clear.

The structures have been given various names by different authors: reproductive sacs or ovarian vesicles (Hall, 1865), graptogonophores (Nicholson, 1866), gonothecae (Hopkinson, 1871), reproductive processes or appendages (Lapworth, 1877), and scopulae, peltae, and saccoids (Lapworth, Elles, and Wood, 1901–1918). Little distinction was made between any of them before the publication of the *Monograph of British Graptolites* when it was pointed out that these sac-like bodies for which the non-committal term Graptogonophores may be used differed amongst themselves and differed in origin whatever their ultimate function. It was shown that there were at least three main types of these graptogonophores: (1) scopulae, (2) peltae, (3) saccoids. The scopulae and peltae are structures characteristically developed in certain Lasiograptidae, and may be closely related since both are external in origin and developed as the result of localization of thickening in the wall of the rhabdosome; the saccoids on the other hand appear to be of internal origin developed as direct outgrowths from the thecae themselves.

The scopulae and peltae differ mainly in the position in which they occur in the graptolite rhabdosome, and are membranous films supported in the case of the scopulae by fibrous filamentous outgrowths, and in the case of the peltae by spines.

The scopulae arise at right angles to the axis of the thecae, and the fibres which bear them are fairly stout and stem-like, are septal (mesial) in origin, and give off or break up into branches or fibrillae, whilst the membranes fade away almost insensibly into the surrounding rock; they may, however, also rise directly from the naked central septal strand well beyond the distal extremity of the rhabdosome. These scopulae appear to be identical with the structures termed reproductive processes by

Hall (1865). They are well developed in certain specimens of *Hallograptus bimucronatus* and its variety *nobilis*; some of these were figured in the *Monograph* (text-figs. 212*a*, *b*; 213*a*, *b*).

Other Lasiograptidae may show ventral (marginal) processes which are typically mesial in origin, though in some cases there may be apertural processes in addition; in all cases they are paired, and in many cases result from the prolongation of the filamentous thickening of the angles of the thecal walls; this thickening may extend backwards to the central septal line. When these ventral processes take the form of paired spines, they may be free as in *Hallograptus mucronatus*, or each pair may support between them a tongue-like membrane, the pelta; such peltae may be seen in *Hallograptus bimucronatus* in addition to the scopulae, and are seen without any scopulae in a specimen of a form at present regarded as a broad form of *Thysanograptus harknessi* var. *costatus* (*Monograph*, text-fig. 215*g*). These ventral processes, however, are not all spines; they may also be fine filaments curved downward so as to unite with adjacent fibres and filaments to form the lacinia, a marginal mesh-work of filaments largely external to the ventral edges of the thecae of the rhabdosome (*Monograph*, text-fig. 215*e*).

In the Lasiograptidae, therefore, graptogonophores of two types may be recognized:

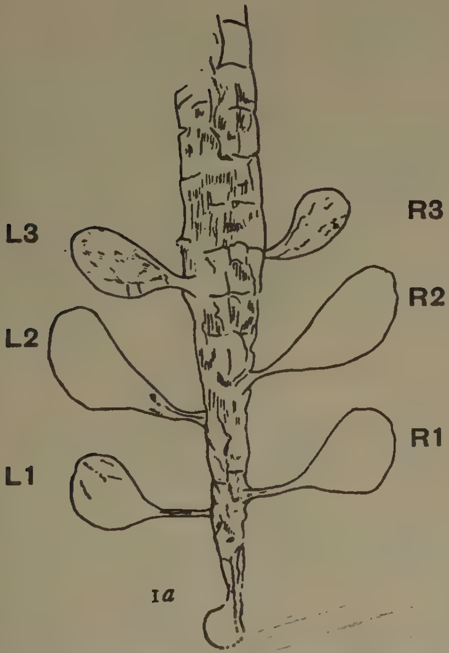
(*a*) Septal (mesial) in origin and position = scopulae.

(*b*) Ventral (marginal) in position though primarily connected with the mesial thickening of certain parts of the periderm wall = peltae.

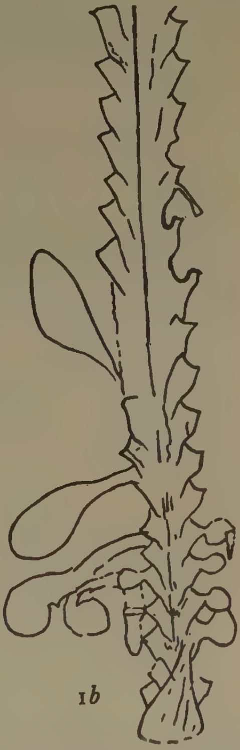
There does not seem to be any positive evidence of the function of either scopulae or peltae; they may possibly have functioned in reproduction as receptacles for the immature siculae produced by some special structure within the rhabdosome; if that were so, the scopulae produced directly from the septal strand had possibly some connection with the nema, the thread-like prolongation of the prosicula, and this must have retained some generative power allied to that possessed by the metasicula which originates from the prosicula. There is, however, so far as I know, no actual proof of this, for though siculae are often found in some abundance on the same bedding planes as the graptolites with scopulae and peltae, they are equally abundant where no graptogonophores are found.

The saccoids though resembling the peltae in position appear to originate differently. The evidence of their being connected with reproduction is also much stronger.

As Bulman (1932) has shown in his figures of certain Diplograpti, siculae are found in such a position as to suggest very strongly their connection with the saccoids; these saccoids appear as definite outgrowths from the apertural region (if not the actual aperture) of certain thecae of the rhabdosome.



TEXT-FIG. 1*a*.—*Diplograptus* (scalariform view) showing graptogonophores of saccoid type. × 5 approx. Dobbs Linn, Moffat. Collection, Sedgwick Museum, Cambridge.



TEXT-FIG. 1*b*.—Proximal portion of *Diplograptus* (not quite in profile view) with graptogonophores of saccoid type, and siculae. × 5. Dobbs Linn, Moffat. Dairon Collection, Glasgow.

In the case of *Cyrtograptus murchisoni* where certain thecae also bear saccoids, the cladium (young individual) bursts through the saccoid as it develops (*Monograph*, text-figs. 351*a–c*). In these cases also the saccoid appears to be a direct outgrowth from the apertural region of the theca, which is not otherwise modified.

The new specimen here figured (Text-fig. 1*a*) and described is one of two parts of the same individual, a *Diplograptus*, which is split approximately down the middle; both parts are seen in scalariform view for a considerable portion of their extent; the graptogonophores, which are well seen in the proximal region, are of saccoid type.

The two portions differ in length, and the saccoids are exceptionally well shown in the shorter of the two which is figured.

Description.—Max. length, 2 cm.; max. width, 2 mm., diminishing proximally. Number of thecae, ten in 10 mm.

On the longer specimen traces of the apertures of five denticulate thecae of *Diplograptus* type may be seen towards the distal extremity on the left side. In the proximal region of the rhabdosome six saccoids are seen, three on either side, and at the proximal termination, as seen, there are traces of a disc (or possibly a seventh saccoid). These saccoids have certain features in common, they are all more or less pear-shaped and attached to the rhabdosome by a strong though slender stalk, and all are directed upward. They differ in size, however, as is shown below.

Dimensions of saccoids (from smaller specimen, Text-fig. 1a)

Left side		*Right side*	
L 3	3 × 1·5 mm.	R 3	2·5 × 1 mm.
L 2	4 × 2 mm.	R 2	4 × 2 mm.
L 1	2·75 × 1·5 mm.	R 1	3 × 2 mm.

The length as measured excludes stalk.

The largest saccoid when seen lying flat appears to measure 4 mm. × 2 mm.

There is a suggestion inside L 2 of bodies which resemble two siculae, but it is not possible to say more, and there are several siculae lying about on the shale.

At first sight the arrangement appears to be regularly alternate, but closer study reveals that this is not the case.

Since the rhabdosome is preserved in the scalariform view, there must be one set of apertures facing the observer in the middle line, and another set in a similar position underneath. In the shorter specimen, the lowest saccoid on the left side L 1 belongs to the underneath, its stalk ending abruptly at the margin of the rhabdosome; the first saccoid on the right R 1 follows directly after L 1, but belongs to the upper surface and the stalk is seen crossing the margin and extending towards the apertural region of the theca; L 2 belongs to the underneath, and R 2 to the upper surface, there being one free theca (devoid of a saccoid) in between it and L 3 which also belongs to the upper surface, whilst R 3 belongs underneath.

The plan therefore is :

R 3 (underneath)
L 3 (above)
Free thecal aperture
R 2 (above)
L 2 (underneath)
R 1 (above)
L 1 (underneath)

These specimens were among a collection of graptolites belonging to the Geological Department of Leeds University, which had been sent to me for identification. Permission to describe and figure them was readily given by Professor Hudson, who has now most kindly presented them to the Sedgwick Museum, Cambridge.

Another specimen from the Dairon Collection of the Glasgow Museum was figured by Bulman (1932), who was mistaken in thinking it belonged to me. It is here refigured (Text-fig. 1*b*) as in its present state it appears to show more than his figure suggests.

The specimen has a length of 3·5 cm. with a maximum width as seen of 2·5 mm. decreasing to about 1·5 mm. at the proximal end ; the specimen is seen almost but not quite in true profile, so that the true dimensions are probably nearer 3 mm. as a maximum and 2 mm. at the proximal extremity. The thecae measure 10–8 in 10 mm. In this specimen saccoids appear to be developed in at least ten of the proximal thecae, four on one side and six on the other, and in several of them their connection with the thecae of the rhabdosome is clear. Almost all the proximal thecae appear to bear or have borne saccoids, though those on the right side as seen are small and globular ; these are probably the remains of those which have fulfilled their function ; some of the saccoids on the left side of the rhabdosome are also small, but there are others higher up which are of more usual size (see above) ; in most of these the relation to the theca is obvious ; there is, however, one still higher up in which the connection is difficult to trace, and here also there appears to be one theca which does not bear a saccoid. Two thecae on the right side are especially interesting, one showing a small globular saccoid connected with a sicula, and the other with a sicula apparently in close connection with a theca.

It seems that true saccoids may easily get broken off from the rhabdosome, for bodies of this nature are not uncommon in the Birkhill Shales of South Scotland (where they have often been referred to *Dawsonia*) and rocks of similar age elsewhere ; moreover they appear at times to have dehisced when free, and swarms of siculae have been noted all round them, some indeed seeming to issue from the portion broken open.

I gratefully acknowledge the assistance given me by Mr. W. D. V. Jones in the drawing of the Graptolites.

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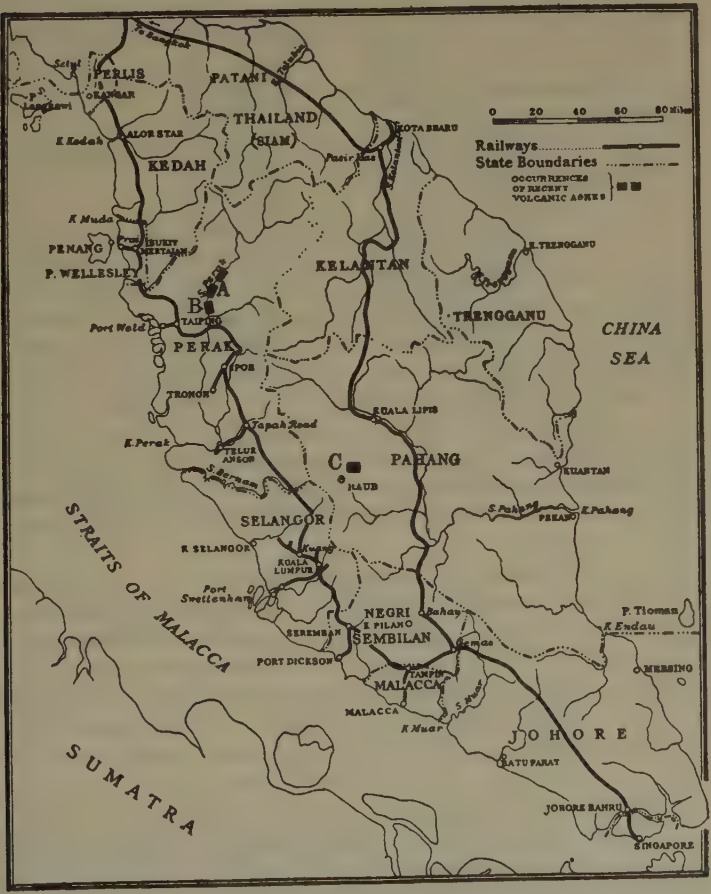
The Organic Content of Recent Rhyolitic Ashes in Malaya

By K. P. Oakley, Dept. of Geology, British Museum (Nat. Hist.)

A SERIES of Recent volcanic ashes and tuffs from various parts of Malaya has been examined on behalf of the Director of the Geological Survey, F.M.S., in order to test the reported occurrence of marine sponge spicules in certain of these deposits (*cf.* J. B. Scrivenor, 1930, A Recent Rhyolite-ash with Sponge-spicules and Diatoms in Malaya, *Geol. Mag.*, lxvii, 385–393,



Text-fig. 1.—Sketch-map of the Malay Peninsula showing the known occurrences of Recent volcanic ashes. (A) Khota Tampan Estate, Perak; (B) Tanjong Perak Estate, Perak; (C) Kampong Dong, Pahang.

pls. xxii, xxiii).[1] If such an occurrence were confirmed it might be taken as evidence of very considerable changes in sea-level within recent times, since at one locality the deposits yielding the supposed spicules reach an elevation of 500 feet above M.S.L. (see Willbourn, *Rep. Geol. Surv. Dept. F.M.S.* for 1937 (1938), pp. 8–10).

The first four samples sent for investigation were as follows (the localities from which they came are shown on the sketch-map, Text-fig. 1) :—

(1) No. 12677.[2] Hard vitric tuff from (A) Khota Tampan Estate, Perak.
(2) No. 12823. Hard vitric tuff from (A) Khota Tampan Estate, Perak.
(3) (Unnumbered.) Soft vitric tuff from (B) Tanjong Perak Estate.
(4) No. 11496. Unconsolidated ash from (C) Kampong Dong, Pahang.

Specimens 1 and 2 were examined by means of thin sections, while specimens 3 and 4 were broken down by boiling in ammonia, and then washed and sieved. No sponge spicules could be detected in any of these samples, nor were there any spicules to be found in two further samples of ash (Nos. 14276–7), collected by Mr. J. A. Richardson at another locality in Pahang and sent subsequently for investigation. The only bodies of organic origin noted at all were in sample 3. This yielded a few diatoms, together with peculiar rod-shaped bodies. The diatoms were kindly examined for me by Mr. R. Ross in the Botany Department at the British Museum. They all proved to be freshwater species.

The problematical rods are composed of opal, bluish-white in colour and translucent ; they vary in diameter from 70μ to 150μ. They are mostly divided into segments by transverse or oblique constrictions (Text-fig. 2A). In any particular rod the segments are of equal length, but there is considerable variation in this respect between different rods. In the more closely segmented forms the intervals between the constrictions are of

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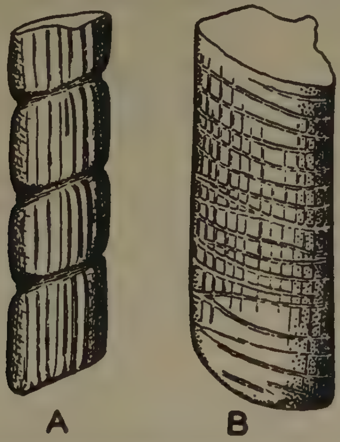
[1] Since Mr. J. B. Scrivenor's paper of 1930 was published references to various occurrences of this deposit in Malaya have been made in the *Reports of the Federated Malay States Geological Survey Department*, 1934, paragraph 33 ; 1937, paragraphs 21 to 28 ; 1938, paragraphs 22 to 25. Additional information regarding exposures in Pahang has been given by Mr. J. A. Richardson in *The Geology and Mineral Resources of the neighbourhood of Raub, Pahang, Federated Malay States*. Singapore, 1939.

[2] Numbers refer to Register in F.M.S. Geol. Surv. Dept.

the order of 70μ, but in some specimens the intervals are 500μ or more. The dominant character of these rods is a fine longitudinal grooving or fluting. The surfaces of some of the rods show minute, flat, oval papillae, each with a shallow central depression, arranged in close-set longitudinal series. Another type, apparently unsegmented, is marked by a bifurcating series of fine, closely spaced, spiral grooves, crossed by the still finer series of longitudinal striae (Text-fig. 2B).

These bodies are certainly not sponge spicules. Moreover, they are far larger and altogether different from the plain monaxon-like rods reported by Mr. Scrivenor in the Perak ashes he examined. There is no animal group to which they might belong, and it seems probable that they are casts of minute tubular structures in some form of plant. The suggestion that they might represent structures in an unrecognized calcareous alga has been put forward, but so far no evidence has been found to substantiate this idea. Another suggestion is that they are siliceous casts of the vessels of higher plants, but there is no proof of this to be found in their morphology. It is hoped that eventually they may be studied by botanists with these possibilities in mind. The silicification of tubular structures in plants growing at the edges of lakes in which fresh rhyolitic ashes were accumulating, or in the hot springs characteristic of volcanic regions, is certainly within the realms of possibility.



TEXT-FIGS. 2A–B.—Opaline rods believed to be casts of tubular structures in some form of plant. × 150. From Recent rhyolitic tuff, Tanjong Perak Estate. Brit. Mus. G.D., V. 26426*a* (A = No. 1 ; B = No. 2 on slide).

Subsequently an examination was made of some of Mr. Scrivenor's original material collected on the Tanjong Perak Estate (*c.* 150 feet above sea-level), including actual rock samples (Nos. 7727–9, 7732),[1] and microscopical preparations (Nos. 7727A–C, G, H, J, K, 7728A–B, 7729A–G, 7732A–C). The rock samples (vitric tuffs) were treated with acid and washed, and the residues mounted in balsam.

Minute spicule-like bodies undoubtedly occur throughout this material, although they vary considerably in abundance from sample to sample. They include short rods, resembling broken monaxons, varying in diameter from 20μ to 40μ (Text-figs. 3C–D); steraster-like forms,[2] mostly about 70μ in diameter (Text-fig. 3A); and, more rarely, spheraster-like forms (Text-fig. 3B) and forms resembling tylote microrhabs (Text-fig. 3E).

A suggestion that these spicule-like bodies are fragments of tubular pumice or volcanic glass is untenable. They stand out in marked contrast to the fragments of volcanic glass with which they are associated, by reason of their lower refractive index. There can be no doubt that they are, in fact, composed of opal, and to this extent resemble unaltered siliceous sponge spicules.

Nevertheless, after careful study of all the material, I have no hesitation in saying that the evidence is wholly against these bodies being sponge spicules. In spite of the fact that the rods are composed of opal (which would imply, if they were spicules, that they had undergone no alteration), none shows any signs of an axial canal, which is an essential and striking feature of the unaltered monaxon spicule of a siliceous sponge. Moreover, amongst the countless broken rods seen in the preparations of the material, no pointed terminations were observed, nor do any of the rods show unmistakable signs of tapering to one end. There is no more than a vague resemblance between the star-shaped forms and Lithistid spherasters. The steraster-like forms are merely globules of opal with surfaces roughened by chemical corrosion. Many of the rods show similar corrosion.

I may add that Dr. M. Burton, who originally supported Mr. Scrivenor's claim, now, after considering the evidence in the light of all the data, is inclined to agree with the view stated above.

After dismissing these bodies as sponge spicules, one is, as a palaeontologist, at a loss to account for their origin. It might be suggested that they are not organic at all, but originated as opaline casts of tubular and spherical cavities in some volcanic glass. Such casts would become loose through shrinkage, and would be released when the enclosing glass was shattered. Some of the fragments of glassy pumice with which these opaline bodies are associated in the Perak ashes do, in fact, show spherical vesicles and tubular hollows of appropriate size; some of these cavities are actually infilled with an indeterminate, semi-opaque mineral, but none has been observed with the opaline infilling. There is thus no positive evidence in favour of the view that the opaline bodies originated in this way. It is, perhaps, worth noting, however, that a few of the opaline rods show a swollen, knob-like termination (Text-fig. 3E). Such a form might have arisen from the infilling of a vesicle which had been partly drawn out into a tubular cavity by flow—a common enough phenomenon in volcanic glass. The spheraster-like bodies might have been formed through the infilling of spaces occurring at the intersections of perlitic cracks in a volcanic glass.

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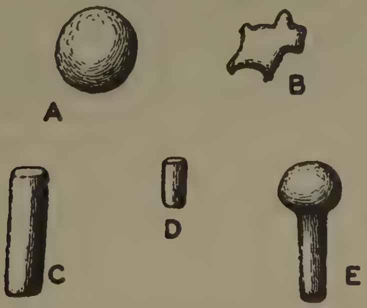
[1] Numbers refer to Register in F.M.S. Geol. Surv. Dept.

[2] Originally recorded as *spherasters* (Scrivenor, 1930, pl. xxii, fig. 4; pl. xxiii, fig. 6.



TEXT-FIGS. 3A–E.—Problematical spicule-like bodies composed of opal. From Recent rhyolitic tuffs, Tanjong Perak Estate. A, steraster-like; B, spheraster-like; C–D, monaxon-like; E, resembling tylote microrhab. All × 150. After Scrivenor, 1930. Original material in Geol. Surv. Dept. F.M.S. (slides 7727–9).

Mr. J. B. Scrivenor, it should be recorded, considers the above hypothesis improbable. He says (*in litt.*): "If there had been an infilling of cavities in the pumice on a scale large enough to produce all these bodies composed of opal I would expect to find large masses of opal . . . but no opal has been recorded yet from Malaya as forming macroscopic masses. A strong objection to the bodies being opal casts of cavities in the pumice is that no opal has been seen in any of the cavities." He points out, however, that opal is a common form of siliceous sinter associated with geysers, and agrees that one possibility is that these bodies, like the larger, segmented rods described above, may be casts of vegetable structures formed in the silica-rich waters of hot springs. He suggests that the monaxon-like bodies, for example, might conceivably represent opaline casts of the cells of filamentous algae such as he has observed in the Malayan hot springs of the present day ; the forms which resemble sterasters and tylote microrhabs might be casts of sporangial cavities in some calcareous alga, but there is no positive evidence in favour of this view, and the spheraster-like forms could not be easily accounted for in this way.

However, whatever the origin of these spicule-like bodies in the Perak ashes, the important fact that emerges is the lack of proof that they have any connection with siliceous sponges either marine or non-marine ; thus, there remains no evidence that the deposits were accumulated under the sea. In fact, the deposition of the ashes under fresh water seems to be assured by the fact that all the diatoms identified in this material are freshwater species.

A Note on the Genera *Staurocephalus* and *Sphaerocoryphe*, with the Description of a New Species of *Sphaerocoryphe*

By J. L. Begg

(PLATE IV)

I. Introduction

THERE has been some confusion between the trilobite genera *Staurocephalus* and *Sphaerocoryphe*. This is probably due to a similarity in the *bulbous* character of the anterior glabellar lobe common to both genera as well as to the genus *Deiphon* and the Australian form *Onycopyge*. King (1920, pp. 532–4), in view of the character of a hypostome of *Staurocephalus* preserved in the British Museum and figured by Salter, was of opinion that this genus should be removed from the Cheiruridae, but hesitated to place it in the Encrinuridae. Raymond, in Eastman's Zittel (1913, p. 725), includes *Staurocephalus* and *Sphaerocoryphe* in his subfamily Deiphoninae, which he defines as Cheiruridae with a bulbous anterior lobe. His diagnosis of *Staurocephalus* is " Glabella with two pairs of lobes behind the bulbous portion. Cephalon with a denticulate border, and pygidium similar to that of *Pliomera* ". *Sphaerocoryphe* has only one pair of lobes behind the bulbous anterior lobe. It is necessary to consider the characteristic features of the genotypes of the two genera.

This short paper was undertaken on the suggestion of Professor W. F. Whittard. Dr. C. J. Stubblefield and Dr. J. Weir rendered assistance with valuable suggestions, criticisms and corrections. Mr. A. G. Brighton permitted access to specimens in the Sedgwick Museum and I have much pleasure in acknowledging my indebtedness and thanks to these four persons.

II. Notes on the Genotypes of Staurocephalus and Sphaerocoryphe

Portlock (1843, p. 257, pl. i, figs. 7*a*, 7*b*) described and figured *Ceraurus globiceps*. A few years later Beyrich (1845, p. 31, fig. 14), erected a genus *Trochurus* (type *T. speciosus* Beyrich) figuring only the pygidium which he stated resembled that of *Lichas*; the cephalon which he also described and assigned to this genus, he remarked bore no resemblance to *Lichas*. Later (1846, p. 10, pl. i, fig. 1) Beyrich refigured his *Trochurus* pygidium alongside another cephalon properly belonging to *T. speciosus* and the 1845 unfigured cephalon he figured (1846, pl. i, fig. 10) as *Staurocephalus murchisoni* Barrande explaining (*loc. cit.*, p. 2) that he had forwarded his proposed 1846 illustrations to Barrande before publication so that he might use the MS. names extant in Barrande's collection. Barrande (1846, p. 52) about the same time published a short description, without illustration, of his genus *Staurocephalus* remarking that the head alone was known to him and the cephalon which Beyrich had in 1845 referred to *T. speciosus* really was *S. murchisoni*. Beyrich's *Trochurus speciosus*, Barrande (1846, p. 54) placed in the synonymy of *Lichas palmata* Barrande 1846 ; this last step was unfortunate for according to orthodox practice Beyrich's name had priority of publication. Barrande referred Portlock's *Ceraurus globiceps* to *Staurocephalus* (1846, pp. 53, 66).

In the year following, Corda (p. 137, pl. vii, fig. 73) figured somewhat diagrammatically a complete specimen of *S. murchisoni* under the name *Trochurus speciosus* Beyrich and Beyrich's Trochurid pygidium he merged (p. 140) into the synonymy of his species *Corydocephalus flabellatus*.

McCoy (1850, p. 401) referred a Rhiwlas trilobite to *S. murchisoni*. In 1852, Barrande gave a series of excellent figures of *S. murchisoni* with a full description and in 1854 the genus *Sphaerocoryphe* was established by Angelin with two genosyntypes.

In 1857 Wyville Thomson described a trilobite as *Acidaspis unicus* from Penwhapple Glen, Girvan.

Salter (1865) figured specimens from Dudley (Wenlock Limestone) Corton, Presteign (Woolhope Beds) and Rhiwlas (Caradoc [= Ashgillian]) as *Staurocephalus murchisoni* and Portlock's *C. globiceps* he refigured as a *Staurocephalus* remarking on the curiously extended pygidial spines ; he also referred Wyville Thomson's species to *Staurocephalus ?* commenting that Angelin's *Sphaerocoryphe* was very near to this. In the same year, Salter's Palaeontographical Society publication gave more generalized versions of his Decade illustrations as well as additional figures including some of *S. ? unicus*. The next step in research is that Schmidt (1881, p. 166) referred *S. ? unicus* to *Sphaerocoryphe*.

Reed in 1906 rightly stated that Salter and subsequently Nicholson and Etheridge had included in *S. ? unicus* cephala which did not belong to this species. He referred these cephala to *Sphaerocoryphe* erecting a new species *S. thomsoni* of which the "Type form" (p. 148) was found in the Drummuck and Whitehouse groups whilst a variety occurred in the Balclatchie group. Wyville Thomson's species *unicus* he referred to *Nieszkowskia.* Reed described the thorax of *S. thomsoni* as consisting of ten segments of which the last "appears to be fused with the front of the pygidium in adult individuals". Reed (1906) also discussed the occurrence of *S. globiceps* at Girvan.

STAUROCEPHALUS Barrande, 1846

Staurocephalus murchisoni Barrande, 1846

Characteristic features.—The cephalon has a semicircular contour which is invaded by the glabella; the cephalic border or limb is broad and flat with a denticulate margin. The anterior glabellar lobe projects for about one half its length beyond the cheek margins. Posterior to the anterior lobe the glabella is convex, much less elevated and reduced to one-half the width, which gives the whole glabella a stalked appearance.[1] Two pairs of lateral oval lobes divide the distance from the anterior glabellar lobe to the nuchal ring into three unequal portions. The cheeks are elevated in the neighbourhood of the eyes, then slope down suddenly to the broad cephalic limb. The axial furrow is broad and deep; posteriorly its course is parallel with the glabella; anteriorly it curves round the frontal lobe of the glabella to the cephalic margin. The facial suture cuts the cephalic border anteriorly close to the axial furrow; its course is almost directly backward to the eye round which it curves. The posterior branch [2] curves outward and backward, cutting the cephalic border a short distance above the genal angle. The occipital ring is broad and separated from the glabella by a well-defined furrow. The lateral and posterior borders unite to form a broad spine at the genal angle; the spine is directed outward and backward, and is extended as far as the second thoracic segment.

Thorax has ten segments; the axis is convex, tapering gently to the posterior segment. The first annulation measures about one-sixth the width of the anterior segment. The axial rings are prominent, the furrows separating them deep and equal in width to the annulations. The pleurae are horizontal and straight for fully one-half their length, then curve at a sharp angle well back, more so posteriorly. The inner portions of the pleurae bear an anterior broad band which is semicircular in section, and behind which there is a narrow thread-like band. The outer portions of the pleurae are furnished at the fulcrum with a facet for articulation and they terminate in long, narrow, pointed spines.

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[1] Barrande describes it as "a kind of neck or cylindrical peduncle."

[2] Barrande's description and his figures (*op. cit.*, pl. 43, figs. 28, 29) of the posterior branch of the facial suture do not agree. He states that its course from the eye is almost at right angles to the mid-line "presque perpendiculaire à l'axe". The figures show it curving out and well backward.

Pygidium is broader than long ; the axis has four annulations, the anterior of which is the largest ; on each side of the axis three lobes are directed outward for about one-half their length, then curve well round becoming parallel with the axis. Posteriorly each lobe is smaller and extended further than its anterior neighbour ; they all terminate in blunt rounded points, forming a gently curving alignment which gives the pygidium a comb-like appearance. A tubercular ornamentation is present on the bulbous, anterior lobe of the glabella and the cheeks ; the antero-lateral limb and the posterior band appear to be smooth and free of any ornamentation. The axial rings and the inner portion of the pleurae bear a single row of tubercles, the outer portion of the pleurae being plain. The three axial rings of the pygidium are also tuberculate.

Remarks.—Portlock (1843, p. 257, pl. i, fig. 7) referred one of the trilobites from Desertcreat, Co. Tyrone, to Green's genus *Ceraurus*, naming it *C. globiceps*. Salter (1865, p. 3) followed Barrande's reasoning and transferred Portlock's species to *Staurocephalus* and later writers appear to have concurred. The type of Portlock's species is badly preserved and none of the specimens of this species from this locality is in a good state of preservation. The description given is brief and the figure is, I think, inaccurate in that the anterior short spine of the pygidium is shown as an extension of the posterior thoracic segment. Portlock states that in the cephalothorax " the central portion or glabella is projecting and globose, and narrowed posteriorly into a kind of neck " ; in the description of the pygidium he says " the caudal facia is rounded ". The affinities of this species are with *Sphaerocoryphe* and not *Staurocephalus*. The globose anterior lobe of the glabella is not stalked and the posterior portion of the glabella is comparatively short. It is evident that two pairs of spines were present in the pygidium, a short anterior pair and a much longer posterior pair. It is only the central post-axial part of the pygidium which is rounded, and this is characteristic of *Sphaerocoryphe*. Portlock's final statement is that " there is some resemblance between the abdominal portion of the fossil and *Paradoxides quadrimucronatus* ". Such a comparison could hardly be made with the *Staurocephalus*-type of pygidium.

McCoy (1850, p. 401) referred a trilobite from the

"Llandeilo" [= Rhiwlas Limestone] of Rhiwlas, Wales, of which only the cephalon was known, to *Staurocephalus murchisoni* Barr. Barrande questioned this identification. I have examined three specimens of this trilobite in the Sedgwick Museum and find that in the largest there are two pairs of lobes posterior to the anterior globose glabellar lobe. These lobes appear detached from the central portion of the glabella and in this respect differ from the posterior lobes of Barrande's species which are not discrete. The horizons of the two forms are not homotaxial, and probably Barrande's opinion at least as regards specific identity should be upheld.

Salter (1865A, pl. vii, figs. 13–20) refers to *Staurocephalus murchisoni* several British examples from the "Caradoc" [= Rhiwlas] rocks of Rhiwlas, N. Wales; Woolhope Limestone and Shales, Corton, Presteign; Wenlock Limestone of Dudley and Malvern. Due to the exigencies of the present war, in the meantime, access to types and figured specimens is of necessity restricted. Comparison with figures is often unreliable. Figures 14, 15, 15*a*, and 16 are enrolled examples, figs. 17, 18 are fragmentary, fig. 13*a* is a complete individual measuring over an inch in length. In comparison with the genotype this specimen has a narrower cephalic limb; the anterior glabellar lobe appears to occupy a further forward position, and there are several other minor differences so that we question if this, or any of the other specimens figured by Salter, should be considered conspecific with *S. murchisoni.*

SPHAEROCORYPHE Angelin, 1854

Angelin (1854, pp. 66 and 67) gives two genotypes, *S. dentata* Ang. (p. 66) and *S. granulata* Ang. (p. 67), both from the *Trinucleus* Skiffer of Mosseberg, Westergotland, Sweden. Miller (1889, p. 567) chose *S. granulata* as genolectotype. Vogdes (1890, p. 146) chose *S. dentata*, but he was apparently pre-dated by Miller. Angelin's description of each species is confined to a single line; *S. dentata* was represented by a young but complete individual, and Angelin's description of it follows immediately upon his diagnosis of the genus. *S. granulata* was represented only by a cephalon and its description follows somewhat later in his work. For these reasons, save for the strict rules of priority, I would follow Vogdes in considering that *S. dentata* should be chosen as genolectotype. Schmidt (1881, pp. 166, 331) considered *Sphaerocoryphe* a subgenus of *Cheirurus* and Reed (1906, p. 146) appears to have adopted that view. King (1920,

p. 146) referred a trilobite from Norber Brow, Austwick, near Settle to *S. thomsoni*, and drew a restoration of the species taking details from his Norber Brow example, but basing the general outline upon Girvan specimens, especially from a nearly complete individual No. I.16047 in the British Museum. In this paper King proposed raising *Sphaerocoryphe* to full generic rank and in his second supplement Reed (1931, p. 23) concurred.

Sphaerocoryphe dentata Angelin

Characteristic features.—The cephalon is semicircular and invaded by the glabella; the anterior glabellar lobe is globose; the posterior portion of glabella is short. The eyes are prominent; genal angles are produced into spines. Neither in Angelin's description nor his figure is there any indication that cephalic spines, other than genal spines, were ever present.

The thorax has ? ten segments. The axis is convex to cylindrical. The inner portion of the pleurae is horizontal and straight; the outer portion shorter and bent sharply back from the fulcrum.

The anterior segment of the axis of the pygidium is produced into a pair of short spines; the second segment bears a much longer pair.

Sphaerocoryphe thomsoni Reed (Pl. IV, figs. 2–6)

As already stated (p. 296) Salter in 1865, and Nicholson and Etheridge in 1878, referred examples of this species to *Staurocephalus ? unicus*. Armstrong and Young (? 1876, p. 16) in their *Catalogue of the Western Scottish Fossils* referred it to *Deiphon forbesii*. Schmidt, and Reed later, recognized its true affinities and placed it in *Sphaerocoryphe* as a subgenus of *Cheirurus*. Prior to 1935, specimens of *S. thomsoni* found in the Girvan district were fragmentary and usually in a poor state of preservation. Since 1935 many complete and well-preserved specimens have been recovered from a slightly higher horizon at the *Starfish Bed* in the Drummuck Group (= Ashgillian), Lady Burn, Girvan.

There is little to add to Reed's description, but his figures (*op. cit.*, pl. xix, figs. 5, 6, 7) are very misleading as they do not represent normal individuals of the species. From more recently collected examples certain features are now known in fuller detail, e.g., a knowledge of the hypostome in both its external and internal aspects. Further, I consider that the specimen from Norber Brow recorded by King varies somewhat from *S. thomsoni* and doubt if it can be considered conspecific.

Description.—In the cephalon the axial furrow, between the overhanging anterior glabellar lobe and the cheek, is deeply incised at that part of its course which lies adjacent to the posterior part of the lobe, but is shallower a little further forward. In the later species *Deiphon forbesi* there is evidence, I think, that a similar shallowing of the axial furrow takes place opposite the eye. This feature will be discussed in our description of the hypostome.

Ventrally the overhanging anterior lobe of the glabella is delimited by a broad, moderately deep furrow which is confluent with the axial furrows ; posteriorly a similar furrow completely circumscribes the whole lobe. In well preserved specimens the eyes occupy a position slightly in front of the posterior end of the globular lobe of glabella.

Thorax.—The thorax has nine segments ; the tenth segment with the two short spines is the anterior segment of the pygidium. The thoracic pleurae are composed of an outer and an inner portion. Reed (1906, p. 147) states that the inner portion bears an articulating facet. In well-preserved specimens this facet is seen to be continued on the outer portion of the pleurae for one-half its length, after which the pleurae curve slightly backward and terminate in broad free spines.

Pygidium.—Reed's description of the pygidium is very complete and his figures (pl. xix, figs. 2, 3) are excellent. He considers, however, that the anterior pair of pleurae of the pygidium, with the short spines, belong to the thorax and have become fused with the pygidium stating " that there is no second pair of pleurae " ; that is to say he considers that the thorax possesses ten and the pygidium one pairs of pleurae. I would make the allocation nine and two respectively.

Hypostome.—The central body is cylindrical and parallel sided for one-half its length or a little more, then it slopes down to its well-rounded posterior end ; towards this end a curved shallow depression traverses the central raised area marking off a narrow crescentic portion. The central area is surrounded laterally and posteriorly by a broad groove and narrow rim ; the border is broadest at the postero-lateral angles. Anteriorly a narrow rim is separated from the central area by a slight depression. When the glabella is removed revealing the hypostome in its natural position, the raised central area now appears deeply concave ; the lateral and posterior walls of this portion rise to a higher level than the surrounding border and into the re-entering angle so formed the deeper portion of the axial furrow appears to rest. At the antero-lateral angles the frontal margin and the lateral rim unite to form a solid projecting process which is oval in section and deeper than broad. This process projects outward at an angle of 90° to the mid line, curving slightly downward for about one-half its length then upward regaining its original level. This process appears to have entered a socket immediately beneath the shallow, anterior portion of the axial furrow, and there can be little doubt, but that it functioned in the articulation of the hypostome. Whittard (1938, p. 120, pl. iv, fig. 7) describes an articulating process in *Encrinurus onniensis*, which, however, proceeds from a slightly more posterior position in the hypostome. From a number of isolated hypostomes of this species it is observed that this portion is often lacking, but in some instances it has been preserved.

Geological Horizon.—Ashgillian, Zone of *Dicellograptus anceps*.

Locality.—Upper Starfish Bed, Drummuck Group, Lady Burn, Girvan.

Material.—Four specimens Nos. BG 7727, 7728, 7729 and 7731.

Remarks.—There is considerable divergence between the *Sphaerocoryphe* from Norber Brow described and figured by King (*op. cit.*) and Reed's species. In the former the central elevated area of the hypostome is elliptical in form or O-shaped. In *Sphaerocoryphe thomsoni* Reed this area is widest anteriorly or U-shaped. It is probable that the notches, referred to by King, immediately beneath the lateral extremity of the frontal ridge, indicate the position of broken off articulating processes. The Norber Brow example has suffered so much from lateral compression that comparison with it is rendered difficult and unsafe, nevertheless, a distinct difference can be observed in the thorax. The pleurae are composed of an inner and an outer portion ; the inner portion is delimited by a tubercular swelling immediately followed by a transverse constriction. The articulating facet which is continued in *S. thomsoni* from the inner to the outer portion of the pleurae is not present in King's specimen. In this latter the outer portion is free for its entire length ; it curves well round and backward, terminating in a long, narrow, pointed spine. These points of difference appear to me to be sufficient to indicate that the two forms are not conspecific.

III. Sphaerocoryphe hastata, sp. nov. (Pl. IV, fig. 8)

Description.—The holotype is a fragment, consisting merely of the left cheeks and a small portion of the anterior lobe of the glabella. Exclusive of the genal spines it measures 7·75 mm. in length, having a width of 5·25 mm. between the genal angle and the axial furrow. The lateral margin of the headshield has a sinuous contour. From the anterior lobe the cephalic border runs outward and backward in a concave curve to about the level of the eye ; at mid-way to the genal angle it is convex becoming concave again at the genal angle. The posterior border of the cephalon is contracted towards the axial furrow ; it curves outward and gently backward with a decided swelling as it approaches the genal angle ; it is separated from the cheek by a broad furrow which dies out towards the genal angle. The lateral and posterior borders are prominent, broad and smooth ; they unite to form a stout spine which curves outward and backward. The point of the spine is not preserved. Immediately anterior to the genal angle there is a single, short, broad, triangular spine ; the basal width of the spine is equal to three-fourths of its length ; it bears a sharp median ridge which gives it a dagger-like appearance. The eye is normal and on a level with the base of the anterior lobe of the glabella ; the facial suture cuts the broad anterior cephalic border at a position directly in front of the eye, making an angle of about 40° to the mid-line ; its course is then directed backwards to the eye round which it curves ; in its posterior branch it first curves gently forward then backward, cutting the cephalic margin in front of the short lateral spine. The axial furrow is deeply incised posterior to the eye, becoming shallower in its more anterior course. The only ornamentation observed is confined to the fixed cheek ; it consists of shallow, round depressions with a few intervening ridges.

Horizon.—*Didymograptus superstes* Shales. Caradoc.

Locality.—Aldons Quarry, near Girvan.

Material.—The holotype BG 2125 is the only example.

Remarks.—This species differs considerably from any species of *Sphaerocoryphe* known to me. A distinguishing feature is the large area of the cephalon which is occupied by the marginal border, especially in the neighbourhood of the genal angle. The most unusual feature, however, is that instead of the two pairs of spines, apart from the genal spines, present in *Sphaerocoryphe*, this form bears only a single spine. This spine is itself characteristic with its broad base, and sides sloping down from a median ridge, not curving downward as is usually the case in this strange genus. The posterior branch of the facial suture takes a less forward course than is usual in the genus, due, no doubt, to the presence of only a single lateral spine. While the text of this paper was in press the writer discovered in Aldons material an isolated hypostome of *Sphaerocoryphe* which may belong to these species.

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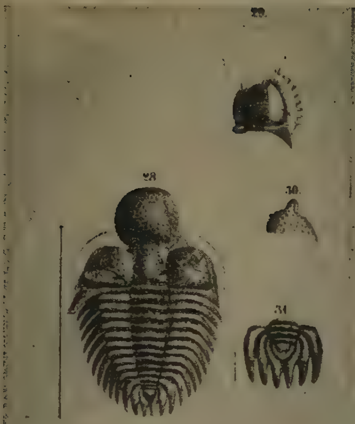
EXPLANATION OF PLATE IV

Fig. 1.—*Staurocephalus murchisoni* Barr. Reproduction of Barrande's figures (1852, pl. xliii, figs. 28–31), same scale.

Figs. 2–6.—*Sphaerocoryphe thomsoni* Reed. fig. 2, BG 7731. A complete individual almost perfectly preserved "Upper Starfish Bed" (Ashgillian) Drummuck Group, Lady Burn, Girvan. × 1½, Begg coll. Fig. 3, a cephalon BG 955, (*a*) indicates the deep part, (*b*) the shallow and less incised part of the axial furrow; same horizon and locality, × 2, Begg coll. Fig. 4, a hypostome in its natural position, BG 7729. The anterior portions of the fixed cheeks are abraded revealing the articulating processes of the hypostome; same horizon and locality, × 1, Begg coll. Fig. 5, an isolated hypostome BG 7730. The anterior articulating processes have not been preserved; same horizon and locality, × 3, Begg coll. Fig. 6, a slab with two specimens in each of which the glabella is removed exposing the hypostome to view. The slab is lit from the bottom right-hand side; same horizon and locality, × 1, Begg coll.

Fig. 7.—*Sphaerocoryphe* sp. Drawing of the Norber Brow example in the Sedgwick Museum based on the internal cast and the external impression. Norber Brow, Austwick, near Settle, × 2.

Fig. 8.—*Sphaerocoryphe hastata* sp. nov. Holotype BG 2151. Dorsal aspect of left cheeks, a posterior portion of the anterior glabellar lobe, the single cephalic spine and genal spine. The genal spine is defective and the pair of small, posterior, glabellar lobes is not preserved. *Didymograptus superstes* Shales. Aldons Quarry, near Girvan. × 6, Begg coll.



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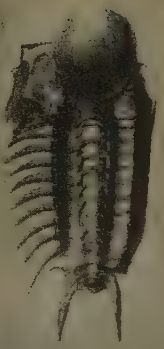

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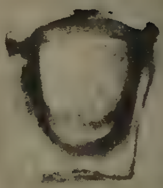

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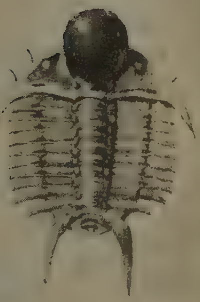

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STAUROCEPHALUS AND SPHAEROCORYPHE

Some problems of Geomorphology and Continental Relationships in British Guiana

By D. W. Bishopp

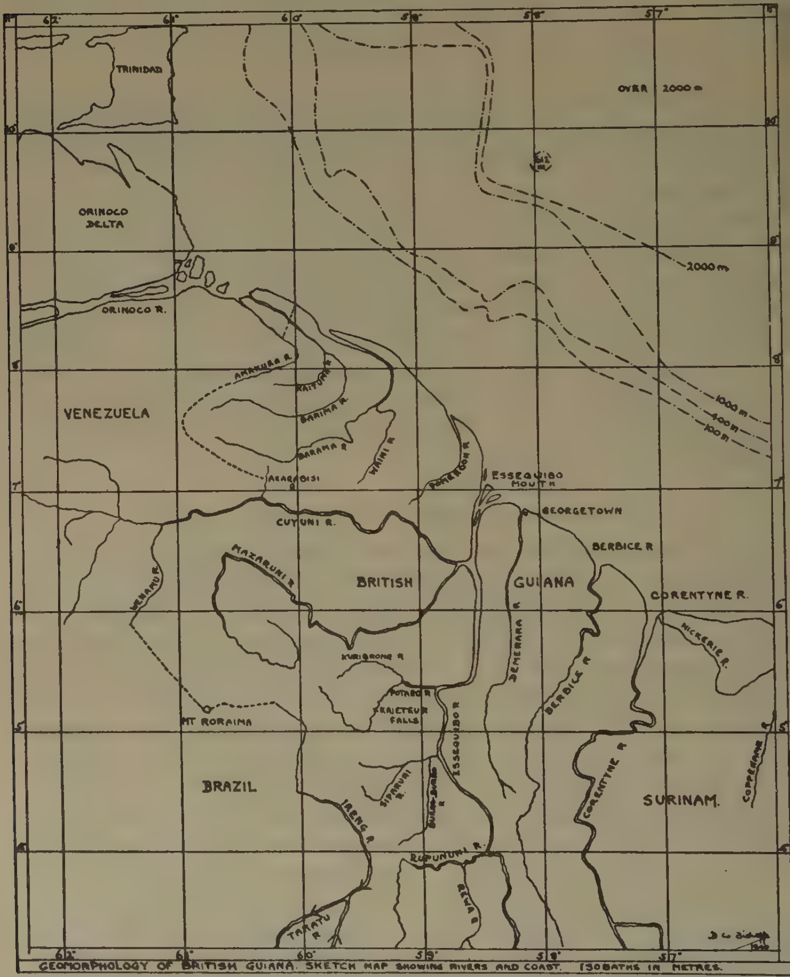
I. Introduction

ALTHOUGH our present knowledge of British Guiana—particularly in detail and in the southern part of the country—is far from complete, it appears timely to attempt a synthesis of some of the major facts that are known. The following account seeks to summarize some of the more pronounced features of form and structure; it raises the question of a large discontinuity or break from south to north along the course of the greatest river—the Essequibo; it seeks to interpret the meaning of the contrasted river-systems west and east of the Essequibo; it raises the question of subsidence in the Berbice Valley, and of the early Amazon drainage; and discusses the problem of continental drift from Africa in the light of du Toit's criteria.

The Modern Land-Surface (*General Summary*)

British Guiana is an integral part of the Brazilian Shield, and nearly all the rocks exposed in it form a crystalline " basement complex ". This implies a reticulated area of granites and granitic gneisses, in which there are set larger or smaller patches of metamorphosed rocks. Most of these are grouped under the general description " The Volcanic Series ", from the prominent group of tuffs, ashes, agglomerates, and lavas of andesitic to rhyolitic character composing them; but they include metabasites, epidiorites, shales, and phyllites, and various types of schist, in some of which staurolite is a very common constituent. A part of the Basement Complex is covered unconformably by the elevated sheet of the Kaieteur Sandstone which forms the mass of the Pakaraima Mountains, a dissected plateau whose scarp-front now lies far behind the present shore-line of the Colony and its plain of marine erosion. The mountains Roraima and Kukenaam on the borders of Brazil, Venezuela, and British Guiana are the highest points of the Kaieteur Sandstone, and in the whole Colony, the height of Roraima being given (Geol. Survey, British Guiana, 1934*a*) as 9,304 feet above sea-level, though another figure is about 700 feet lower. Both the sandstone and the crystalline complex are invaded by extensive sheets and dykes of non-foliated and generally very fresh gabbro and dolerite.

The rocks of the Basement Complex show marked differential erosion, the granites forming relatively flat depressed areas, while the Volcanic Series, metamorphic basic rocks, and dolerites stand up sharply in contrast, so that in spite of the thick forest, the characteristic "weathering pattern" of a landscape gives a good clue to the geology when viewed from an aircraft.



The Geomorphology of British Guiana: Sketch map showing rivers and coast, isobaths in metres.

Toward the coast, however, the rugged relief in this system of rocks, which may attain an amplitude of 1,500 feet or more, smoothes off to an intermediate peneplain characterized by the presence of isolated platforms or sheets of laterite. Their level descends gently from a maximum of about 700 to 800 feet to a height not much above that of mean sea-level. This does not necessarily apply to lateritic cappings formed in situ on higher hills.

This intermediate peneplain plunges at a gentle angle below a covering of Quaternary or perhaps late Tertiary unconsolidated fluvio-marine sands and clays known as the White Sand Series, which also contains lignitic bands. Between this series and the Basement, and very little above sea-level, are the great and important deposits of bauxite for which British Guiana is famous. The lateritic platforms of the intermediate peneplain are considered to have been formed on islands in the sea in which the White Sand Series was deposited.

The greatest known height attained by the base of the White Sand Series in the interior of the Colony is about 600 feet above sea-level ; but nearer to the coast, and when approaching the meridional valley of the Berbice River, it falls toward sea-level and is in turn covered by alluvium of modern origin : sands, clays, muds, and vegetable remains.

The intermediate peneplain has been described as a slightly elevated and undulating horizon (Geol. Survey, British Guiana, 1934*a*), representing an old plain either of marine origin or of mature erosion at sea-level. Its height is nowhere known at present to exceed 800 feet above sea-level. The present rivers and their tributaries have entrenched themselves into this plain, removing much of the superficial covering and some of the solid rocks. Isolated hills which were formerly rocky islands projecting above the sea rise above the general level ; but wide sand flats and many ridges and watersheds have about the same height, in that they lie on lines of uniform uplift. The intermediate peneplain is almost entirely forest-clad except for savannahs near the heads of the Essequibo and Rupununi rivers.

The high Pakaraima plateau whose edge formed the coast of the ancient sea which covered the intermediate peneplain, is now 130 miles from the present shore-line. Its top ranges from about 1,200 to 3,500 feet above sea-level, with exception of the high " inselbergs " of the Roraima region in the western portion of the Colony. The rocks of this plateau are principally Kaieteur sandstone and intrusive dolerites and gabbros ; much of the region is forest-clad, there being some savannah and grassy mountain sides with forest in the valleys. Other high lands in the Colony are the Imataka hills in the North-West District, between 800 and 1,500 feet; the Kanuku mountains and other ranges in the south-western portion of the Colony are said to rise to 2,000 feet. Precise observations in this region are scarce, though the British Guiana–Brazil Boundary Commission has done some work here. It would appear from aircraft observations that there are higher peaks in the southern portion of the Colony. Both the Imataka and Kanuku hills are composed of Basement rocks.

II. The Continental Shelf and the Present-day Coast

The foregoing summary would be incomplete without reference to the continental margin. There are certain gaps in the hydrographic work which, one may hope, may be supplemented at a future date; but a study of the charts shows that, in general, the edge of the shelf between the 100- and 400-metre isobaths rather closely parallels the present low-lying coast, and the shelf is covered by a wide expanse of fairly shallow water. Its breadth to the 100-metre isobath is between 80 and 90 miles, though rather less off the Waini mouth; but the transition to the 400-metre line is relatively abrupt, and the 2,000-metre line appears to fall about 30 miles to seaward of this in the neighbourhood of British Guiana. It does not, however, closely follow the edge of the shelf east of Trinidad and north of the Essequibo; and the significant alignment of the submarine precipice which cuts the 10th parallel, with the notches in the 100 and 400-metre isobaths, and the course of the Essequibo River, will immediately be apparent. This is discussed later.

The gradient off the shelf north-east of the Corentyne region is as much as 1,000 metres in 10 miles, or about 1 : 16. To the north-westwards it flattens considerably, attaining its minimum value north-east of the Orinoco Mouth, but becoming almost precipitous east of Tobago. The first declivity is generally between the 100-metre and 1,200–1,400-metre isobaths, but 180 miles north of Cayenne there is a deep of 4,000 metres, and an elliptical trough whose major axis is west-north-west near Lat. 8° N. and between Long. 55° and 56° W. At 58° W. and 9° 20′ N., off the Essequibo, there are depths of 2,500 to 2,900 metres, and it will be noticed that north of parallel 9° N. and east of, say, meridian 58½° W., oceanic depths up to 4,000 metres are rapidly reached. Here there is a second sharp declivity from the 1,000-metre isobath downward. It is clear that if the Guiana Coast received the small elevation of 100 metres (about 330 feet) the feature of a "shelf" would be almost eliminated. On the other hand a depression of about the same amount would bring the relations of land and sea almost back to what they were in White Sand times.

British Guiana has a sea-board trending in a south-easterly direction over a distance of about 270 miles. The coastal alluvial belt is some 15 to 30 miles wide; it is flat, swampy, and is occupied by a certain amount of wet savannah and by belts of courida and mangrove which extend into the foreshore. The superficial and coastal deposits are sands, muds, and silts; occasionally scanty beach deposits of shell-gravel and fine micaceous sands are formed on the muds a little below high tide mark. Sand lenses in the alluvium are valuable sources of artesian water, whose head, as Harrison has pointed out, is counterpoised by the difference in densities of fresh and salt water.

III. SEDIMENTATION IN RIVERS AND FORESHORE

The scope of this paper permits but a short mention of modern sedimentation, which is, however, of paramount importance in the domestic economy of the country, owing to sea defence problems. The waters of the rivers give some indication of the character of the rocks over which they pass. Small streams rising in areas occupied by the Basement rocks or dolerite are as a rule fairly clear, except where weathering shales and clays give rise to turbidity. Those derived from White Sand, sandstone, wet savannah regions and sometimes from sandy granitic areas are known as "black water", being quite clear but of the colour of strong tea, as is common in peaty and siliceous terrains. Harrison has drawn attention to the appreciable amount of silica carried in solution in the waters of British Guiana.

The muddy shallow coastal waters over the continental shelf are exposed to the north-east trade-winds, which cause a perpetual drift of current and sediment in a north-westerly direction along the coast. The origin of this sediment will be discussed in a succeeding paragraph. In consequence of this current-drift there is a systematic deflection of the river-mouths to the north-westward. This process is not developed to a uniform degree on all parts of the coast. The greater rivers of British Guiana—excluding those which enter the Essequibo at some distance from the sea—have a northerly course to the Caribbean: they are the Corentyne, Berbice, Demerara, and Essequibo. In their estuaries there is a building up of sediment on the right (east) portal or bank of the sea-mouth, and a scouring of the gap to the westward. This is very much accentuated in the case of the rivers in the North-West District between the Essequibo and Punta Playa: the Pomeroon, Waini, Barima, and Amakura. Their average course is north-easterly, and toward the coast it is actually deflected through more than 90° to the north-west, by the progressive building-up of spits and banks on the right-hand or seaward side; so that the lower parts of the tidal reaches of these rivers flow parallel to the present coast-line and at no great interval from the sea, for considerable distances. This state of affairs is also reproduced at the Surinam coast between the Marowijne and Corentyne rivers, but not so in Cayenne.

The part played by the Amazon as a source of drifting sediments in these coastal waters is somewhat obscure; but considerable work on sedimentation and hydrographic survey has been, and is being carried out in connection with sea defences in British Guiana. I am indebted to Mr. G. O. Case, Director of Public Works, for some information on the rivers between the Corentyne and the Essequibo. It would appear that these rivers, even at considerable distances above their mouths, carry no appreciable quantities of silt and mud; they are in fact comparatively clear. They do, however, transport considerable quantities of sand, which can be observed from an aircraft, moving in a somewhat turbulent manner at the zone of bottom carriage. This sand forms shifting water-dunes, banks, bars and islands at the mouths of the four large rivers in this part of the coast. It is evident that some mud from turbid rivers such as the Puruni, far inland, must be entrained in this shifting sand; but its presence is not in evidence when the river meets the tidal region.

The rivers of the North-West District, however, definitely do carry a fair amount of mud in suspension; this is disposed of between the swampy regions, choked with vegetation, and the shore waters, and is discernible in the formation of the "guard-banks" already described on the seaward side.

At the date of writing, the building of groynes, to check the shore currents and so precipitate mud to form a foreshore and resist coastal erosion, has been successfully carried out. Much of the mud now suspended in the coastal waters appears to be in a state of oscillation, now precipitated and now thrown suddenly again into suspension, perhaps by irruptions of the arteian water in the coastal beds. It seems doubtful whether there is any steady gain or loss in deposition of mud off the coast of Demerara, except through artificial causes, though deposition appears to be increasing off the north-west coast.

IV. THE RIVER SYSTEMS AND DRAINAGE OF BRITISH GUIANA

An analysis of the river systems of British Guiana provides a fascinating and instructive study. It divides itself naturally into two contrasting sections :—

(i) The Essequibo–Corentyne section, east of the Essequibo.

(ii) The drainage west of the Essequibo. This section is subdivided into two parts : the seaward drainage north of the Cuyuni River, and that into the Essequibo south of the Cuyuni River.

(i) The most striking feature of the present surface is the approximately parallel northward drainage of the Corentyne, Berbice, Demerara, and Essequibo Rivers, in contrast with that west of the Essequibo. They rise on the Amazon divide, apparently at no very great altitude, and flow entirely over the crystalline Archaean basement until they reach the White Sand series and the recent sediments of the coast region. Their navigation is impeded by innumerable rapids and low falls ; some, though by no means all, of which are caused by bars of rocks resistant to erosion, such as the dolerite dykes. The relationships of these rivers with structures in the Basement series are not clear, since the mapping of the latter is not complete ; and there is not necessarily any simple tectonic arrangement in the latter. From the greater portion of the areas drained by these rivers the Kaieteurian formation overlying the Basement is completely absent ; it is known only as a great elevated and escarped platform west of the Essequibo and south of the Cuyuni, and as outliers to the east of the Corentyne in Surinam.

(ii) Drainage systems west of the Essequibo. These are in noteworthy contrast with those to the east of that river. They all flow generally eastwards into the left bank of the Essequibo, with exception of those connected directly with the Caribbean Sea. The two great rivers Mazaruni and Cuyuni and their tributaries bring water from the west and south-west to their confluence 5 miles from Bartica, where they join the Essequibo. The Cuyuni thus cuts this western region of British Guiana into two halves from east to west, and the southern half contains the Pakaraima plateau with its tremendous series of high waterfalls of which Kaieteur is the best known. The Cuyuni itself rises outside the boundaries of British Guiana, well within Venezuela; its average course in British territory is very nearly from west to east, and lies a little below the parallel of Lat. 7° N. On its right bank the Wenamu, a large tributary flowing northward, defines a portion of the Guiana–Venezuelan border; the corresponding boundary on the left bank much lower down stream is demarcated by the Akarabisi which flows southward. The angle between the Wenamu and the Cuyuni is occupied by an elevated block of the Kaieteur Sandstone, the river having cut through to the Basement series at the foot of the scarps. The Kaieteurian rocks are not known at present to occur in British territory north of the Cuyuni. The north or left flank of the Cuyuni Valley is comparatively narrow, and the broad territory on the other side of the watershed, between its rim and the sea, is now to be considered.

(ii*a*) *Drainage North of the Cuyuni River*

The major rivers in the region comprising the North-West District of the Colony all make their way into the Caribbean Sea. These are the Pomeroon, Waini, and Barama, Barima, Kaituma, and Amakura. None of the land in this district is very high; the watersheds rise generally to a few hundred feet above sea-level, with occasionally higher peaks, but the writer has no information on that portion of the border between Akarabisi and Amakura Heads. The gradients of these rivers are comparatively low, particularly in the lower reaches; on the Barama the limit of tidal effect is said to be at Tasawini, which is at least 100 miles as the river goes, from Waini sea-mouth. It is at any rate noticeable above the Waini-Barama confluence. In the coastal regions there are great areas of wet savannah and courida and mangrove swamp, barely above sea-level; from the Moruca to the Baramanni one can have the curious experience of travelling by boat up one river and down another without noticing any apparent watershed. Notwithstanding the low-lying character of the greater portion of this region, there are a number of falls and rapids in the upper reaches of Waini, Barima, and Barama.

It is convenient here to describe certain physical features of the upper parts of the Barama and Barima rivers. Most of this portion of the country lies below 500 feet above mean sea-level; the higher ridges and watersheds appear to consist mainly of basic metamorphic rocks on a granitic pediment which may either be gneissic or non-foliated. There are, however, in the upper Barama Valley, and south of the Barama–Cuyuni watershed, a number of isolated hills or "inselbergs" which carry laterite caps at an altitude of 700–800 feet above sea-level; one of these is at Cassmaparu Creek 2 or 3 miles north-east of Towakaima; there is another on the left bank of the river some 25 miles west of and above Towakaima; another a little south of Arawanta Mouth some miles below Towakaima (on the Barama); others south of the Barama–Cuyuni watershed are in the neighbourhood of Iroma and Noseno Heads. The watershed between Barama and Barima at Hyma Hill on the track from Towakaima to Arakaka is 600 feet high, and at this particular point there is no laterite. The laterite is apparently not directly related to the underlying rocks, but it certainly seems to have some relation with the outlying caps and sheets found between 400 and 450 feet much farther to the east in the Cuyuni Valley, e.g. at Quartzstone. These are supposed to have been formed on islands when the rest of the country was covered by the White Sand sea. There is no trace of the White Sand in the Barama and Barima regions; the occurrence at Aranka is the highest and most westerly of any at present known in the Colony. The low-level bauxite in the Demerara and Berbice rivers may therefore represent this laterite sheet descending to the eastward.

The Towakaima Falls in the Barama River have three main cataracts and a drop of some 80 feet in half a mile. They flow over a composite granitic gneiss, and appear to be caused by a general shelf or platform in the peneplain, the top of the falls being taken at 310 feet above mean sea-level (by aneroid). Some 25 miles to the north of them the Barima passes over the Eclipse Falls; while to the south of Towakaima the low escarpment of the falls on the Barama forms a watershed between two tributaries running northward to that river: one enters the Barama a little above the falls; the other, running along the foot of the escarpment, a little below it. The Eclipse and Towakaima falls and the Apurakuni below the shelf of the latter are significantly aligned with the large Iroma river flowing south-easterly into the Cuyuni. The shelf indicated may be the edge of a platform of erosion, or even a fault-scarp; but there is no evidence which would suggest the latter.

It will be noticed that although, owing to the low gradients, the courses of the six main rivers of the North-West District are extremely tortuous, they are in the main north-easterly and sub-parallel, until they leave the crystalline floor and pass on to the coastal sediments. That is to say that the Pomeroon, Waini, Barama, Barima, Kaituma, and Amakura Rivers, and the upper or Venezuelan portion of the Cuyuni River, all have a trend which is not very different from that of the main Orinoco. The upper portion of the Barama flows east-south-east to south-east as far as Towakaima Falls: down to this point it is a strike-stream conforming closely with the trend of foliation (about 130°–140°) in the considerable area of granitic gneiss which it traverses. On reaching the coastal alluvials the swing of the river-mouths to the north-westwards will be remarked, as described on an earlier page.

It is considered that these coastal sediments are not very thick in the region of Waini Mouth at the north-west corner of the Colony; and to the south-east of this, inliers of the Archaean floor appear at various points not very far from the coast: e.g. at Issororo; Mount Everard; near Baramanni; and Santa Rosa (Acquero). The coastal sediments tend to be thin until they approach the Berbice syncline east of Georgetown. There is a tendency in the North-West coastal district for the ancient floor to form ribs or ridges like fingers extending to the north-east under the wash of alluvium. Probably this structure is reflected in the north-easterly courses of the rivers.

(ii*b*) *The Drainage South of the Cuyuni and West of the Essequibo*

In this region the Mazaruni, Potaro, and Siparuni Rivers take charge of the main drainage from the Pakaraima Mountains. This high plateau has also a peneplained character. The edge of the Kaieteur sandstone provides some of the highest major waterfalls in the world: of these Kaieteur (741 feet), Amaila, King Edward VIII, Princess Marina, Purupuruni, and Achipomu are the principal, while Art's Fall, Kulishiri, and Sabrek are much smaller but still high. There is no evidence of marginal faulting; but the true thickness of the sandstone formation is obscured through its injection by huge gabbro sills, which may be responsible for the elevation of a good deal of this plateau. G. J. Williams has discussed the question of pre-White Sand morphology (1936) and rejects the hypotheses of fault-scarps bounding the Pakaraima plateau as it exists at present, but points out that if there were a downthrow on the seaward side one would expect to find sandstone at low altitudes in the lower parts of the Colony; and if an upthrow, the complete removal of an extensive sheet of sandstone over the lower part of the Colony. We shall return to this point later.

The extraordinary course taken by the upper part of the Mazaruni is noteworthy. Between its source in the Merumé Mountains and the Tiboku rapids, it has passed through changes of direction in a clockwise spiral aggregating to 360° ; only when it falls below the sandstone plateau does its east-south-easterly course above Tiboku along the foot of the escarpment become strongly established. The territory between the Mazaruni and Cuyuni rivers is partly drained by the Puruni with its principal tributaries the Kartuni and Pashanamu. The Puruni for a considerable distance also has an east-south-easterly course and is thus roughly parallel to the two major rivers on each side of it. In this section it flows over the Basement rocks and appears to be a strike-stream ; but near Mara-Mara and Tiger Creeks it breaks away to the southward and joins the Mazaruni. The big quadrangle thus formed between Tiboku (Mazaruni), Puruni Mouth, Mara-Mara Creek, and Paiyuka Falls (Puruni) is occupied by the Sororieng Mountains, a rugged area which appears to be occupied by a great development of dykes and sills of the later gabbro-dolerite. Most of these seem to dip radially inward, forming a structural basin, but culminating topographically in Sororieng Peak, which is about 2,500 feet high. It is not known, however, if there is any sandstone here, similar to that which caps the escarpment south of it on the opposite bank of the Mazaruni.

To the south of the Mazaruni the principal rivers flow from south and west into the west (left) bank of the Essequibo. These are :—Potaro ; Siparuni, and Burro-Burro ; Rupununi, Rewa, and Quitaro ; Cuyuwini and Kassikaityu. The Takatu on the western boundary of the Colony runs northward and parallel with the Rupununi for some distance, but at its confluence with the Ireng its direction is reversed south-westwards so that it joins the Amazon system via the Parima. The relations of the Rio Branco, of which the Takatu is the upper portion, with the headwaters of the Essequibo, are also discussed by Passarge (1931), who suggests that there is a case here of river-capture, the Takatu having once been a headstream of the Essequibo.

Schomburgk (1840–4) indeed has pointed out that the low altitudes and close proximity of the Rupununi and Ireng rivers, together with the intervening Lake Amucu, bid fair to make a continuous internal waterway between Georgetown and the vast tracts of sub-equatorial South America. The results of the recent Boundary Commission Survey of the south-eastern portion of the Guiana–Brazilian frontier are not available, but it is understood that while there is some rugged and lofty country at points between the heads of the Corentyne and Essequibo Rivers, the divide between the former and the Amazon drainage system has a low altitude. The evolution and morphology of these vast river-systems provide not the least interesting problem of the South American continent. Comparatively little can be said regarding the region of crystalline Basement rocks extending to the Brazilian border south of the Rupununi River, since it has been insufficiently visited and studied.

V. THE WHITE SAND BASIN

We take now the Essequibo–Corentyne area, already conspicuous for the contrast between its drainage systems and those of the territory west of the Essequibo. Here the White Sand Series and the overlying alluvials make a considerable embayment from the sea-coast southward into the interior of the country, where the peneplaned Basement surface with its overlying mantle of bauxite deposits plunges at a low angle beneath the unconsolidated sediments. The outcrop-breadth of the latter is least near the Essequibo and Corentyne mouths—the sea-coast being the other boundary—and widest between the coast and that point where their southern margin is cut by the Berbice River. The sediments in this region form a flat funnel-shaped synclinal or downwarp, which has a south-to-north axis approximately coinciding with the Berbice River, and pitching gently northwards. The flanks of the synclinal dip gently inwards toward the Berbice River and the coast.

The relicts of the White Sand, however, extend far beyond the limits of that area between the Corentyne and Essequibo mouths and Kuruduni on the Berbice River, where the Basement rocks are completely covered by the unconsolidated sediments. West of the Essequibo the White Sand is met as a chain of thin sheets and outliers whose height rises steadily to the westward. Near Aranka north of the Cuyuni River its basal height is 600 feet above mean sea-level, the highest yet recorded in the Colony. Near Aremu, south of the Cuyuni and east of Aranka, it is 400 feet and shows a steady fall to the eastward of some 9 feet to the mile. The hill of fine white sand at Waramuri, in the tidal portion of the Moruca River near the coast, appears to belong to the White Sand Series, in which case its base there would be a little below sea-level. At Sandhills on the Demerara River its base is less than 50 feet above the same datum. It has been recognized as far south as the Rupununi–Essequibo confluence; and from there the limit of the White Sand patches and outliers describes a large arc to the north-east into Surinam.

Boreholes on the coast between Suddie and Georgetown have shown that the coastal sediments deepen toward the east, the greatest recorded depth being 1,680 feet a little east of Georgetown where the hole is said to have bottomed in crystalline rock. Harrison calculated that the coastal alluvials would have a maximum depth of about 3,000 feet near the Berbice Estuary; but the whole question, at the time of writing, is fortunately on the way to being settled by the seismic work, to be supplemented by drilling, which has recently been inaugurated. This is to ascertain whether there is room for any petroliferous Tertiary or Cretaceous sediments to have been buried here.

Grantham and Noel-Paton (1937) have summarized some morphological aspects of the White Sand Basin, and some of their conclusions are best quoted verbatim :—

> "The simplest explanation, and the most probable, is that the White Sand was laid down in a shallow sea or estuary on a nearly level floor. Prior peneplanation of the whole country (seaward of the Kaieteurian scarp) is an accepted fact from the form of the crystalline rock floor on which the White Sand rests. A Berbice-Corentyne geosyncline may already have begun and was being filled by coastal sediments; further subsidence of the geosyncline caused the inundation of the area now occupied by the White Sand series."
>
> "After the completion of the deposition of the White Sand the geosyncline continued to deepen, the rims being uplifted above sea-level . . ." (to a height now known to be as much as 600 feet, D.W.B.) . . . "while the coastal portions were depressed."

The roughly semicircular embayment of the unconsolidated rocks from the mouth of the Essequibo to the Corentyne, and extending into Surinam, has been noted :—

> "Such an outcrop can mean one of two things: an infilled topographic basin or a geosyncline. The uplifting of the White Sand deposits inland and the depression of coastal sediments to over 1,680 feet below sea-level on the coast involves some tectonic movement. A minor geosyncline complementary to that of the Orinoco has been suggested above."

The course of the middle portion of the Berbice River suggests the position of the axis of such a syncline. It must be realized that the 1,680 feet below sea-level is a minimum figure which may attain at least double that value.

> "Bays" (in the White Sand) "appear along the main rivers and notably the Essequibo and Potaro. . . . Whether the bays be depositional or tectonic they have influenced the present courses of these rivers." . . . "An alternative hypothesis is that the Berbice-Corentyne basin was eroded sub-aerially and

> that it was submerged as such without folding. The White Sand sheet may then represent a deposit lying in its original place of deposition but uplifted. Harrison mentions the probability of a large old river channel now deeply submerged north of Berbice. The present courses of the higher Essequibo and Corentyne rivers and of the rivers now flowing into the Amazon, e.g. the Ireng and Takatu, suggest that they once flowed into the Berbice River. On the other hand, the uniformity of thickness of the White Sand, the absence of homotaxial change and the shape of the lateritic benches to the islands are opposed to this hypothesis."

In the work quoted above, the altitudes appear to refer to the exposed top of the White Sand surface. The actual thickness of the White Sand is not great, the order of magnitude being 100 to 150 feet. The present writer has referred all altitudes to the base of the White Sand.

VI. TECTONICS AND LITHOLOGY

The straight broad channel of the lower Essequibo with its consistent northerly course is a striking division between two geological provinces. To the east of it, along the parallel Berbice channel, there is an axis of depression oriented from south to north. The lower Essequibo is also significantly aligned with the inflexion in the edge of the continental shelf and the western lip of the deep oceanic basin which lies to the east of it. The region to the west of the Essequibo not only contains the high Pakaraima sandstone plateau of the present day, but formed a physical barrier—a coast-line—as indicated by G. J. Williams, who has shown the existence of pre-White Sand river-channels, e.g. the proto-Mahdia, and of an ancient shore-line in the Potaro district. The contrast between the drainage-systems east and west of the Essequibo has been pointed out earlier in this paper.

While the Basement rocks and their associated minerals appear to be similar both east and west of the Essequibo, it will be noticed that no significant deposit of the magmatic type of minerals is known in British Guiana east of the Essequibo. Practically (though not entirely) all of the production of gold and diamonds comes from the westward of this river; also some unimportant mica-bearing pegmatites and occurrences of manganese ores. These minerals lie both close to the river and at all distances to the west of it, and the mineral-bearing province continues in this direction far into Venezuela. The manganiferous phyllite or shear-belt striking east and west at Saxacalli on the lower Essequibo does not apparently cross the river to its eastern bank. The generalization regarding the relative lack of minerals of magmatic origin to the east of the Essequibo, as far as the

Corentyne, appears to be fair at any rate as far south as Lat. 5° N., or perhaps even 4° N.

There are occurrences of gold in Surinam east of the Corentyne, but these are not here relevant. A good deal of the gold west of the Essequibo is alluvial, but it appears to be directly associated with the margins of granitic masses or of Basement rocks in contact with them ; while the alluvial diamonds are generally regarded as having been weathered out of the Kaieteurian sandstone.

By contrast, most of the valuable superficial deposits—those of bauxite—are highly developed in the Essequibo–Corentyne region, but hardly at all to the west of the Essequibo.

It must also be noticed that, so far as is known, the Kaieteurian Sandstone is entirely absent from the Essequibo–Corentyne tract. It does, however, occur in Surinam at the Tafelberg, and its presence as three small outliers at a low level on the east bank of the Corentyne is indicated by Ijzermann (1931).

The conclusion that the channel of the lower Essequibo marks an ancient tectonic break of considerable magnitude cannot be lightly set aside. It is not suggested that it can at present be identified with a fault of considerable throw, but that it may represent a crack or fracture-plane along which considerable movements, not always in the same direction, have taken place. The tectonic depression of the Berbice district may therefore not only be due to down-warping along the south-north axis parallel to the Essequibo, but to hinging down toward the sea by movement along the supposed " Essequibo break ". In such case there is at least a chance that Kaieteur sandstone, as well as later Tertiary rocks, may cover the crystalline floor under the deep alluvium ; and the results of exploration here may be looked forward to with great interest. The length of the Essequibo " break " must be at least three degrees of latitude, and the arguments in favour of its existence are, briefly :—

1. Its alignment with the edge of a deep ocean basin on the declivity of a continental platform which closely parallels the present coast line.
2. Its position as a well-defined dividing line between two geological provinces which differ in several respects. These are, in topography ; in character of drainage systems ; in certain lithological and mineralogical aspects.
3. Its position in marking the former locality of a coast line opposite what is now a tectonic depression.
4. Its conformity with certain " fault-line coast " criteria to be discussed in the succeeding section of this paper.

It is probable that G. J. Williams's rejection of a fault-scarp hypothesis has been justified in the case of the enormous cliffs which form such an impressive escarpment for many miles on the right flank of the Mazaruni Valley. At the same time, later work in this region has shown the development of sheets, dykes, and sills of post-Kaieteurian gabbro-dolerite to be enormous, and one wonders to what degree these large intrusions have been responsible for block-movement and tilting in the Pakaraimas. Further, the criteria for fault-line scarps, which were here judged by Dr. Williams to be absent (vide sect. ii*b*), are not after all so remote. There is a " step " in the Basement rocks within 100 miles of the escarpment: that indicated by the Towakaima Falls in the North-West District; though there may be some doubt as to the significance of this point. What is much more important is that there is in fact the complete absence, which implies no doubt the removal, of the sheet of sandstone from the region between the Corentyne and Essequibo rivers. That would suggest an upward movement and erosion of this block; the Essequibo and Corentyne being taken as its west and east boundaries respectively. If, however, a movement had been downward, there may still be Kaieteur sandstone buried under the deeper parts of the Berbice alluvium. But it must be borne in mind that both consecutive elevation and depression, including a seaward tilt to the north, may have taken place, and that the position of the present day is merely the resultant of these movements. Harder indeed suggests (1936) that a pivotal movement may have taken place with elevation in the south, and depression in the north of the Colony. On the other hand the " Essequibo break " may well be a " tear " with considerable horizontal and relatively little vertical displacement, and this idea is supported by the known occurrence of north-to-south tear-faults in the Orinoco–Trinidad region. This will be examined in the succeeding section on Continental relations.

It is an extremely difficult matter to come to any general conclusion regarding the regional " grain " of the crystalline rocks of the Colony. The position is by no means so clear as on the Gold Coast, where the north-easterly trend dominates the tectonics.

In British Guiana, observations are still missing over large areas. The North-West District shows a predominant north-west to south-east strike, which is sometimes modified to an east–west direction. One cannot tell whether such strikes are " ripples " so to speak, of the Orinoco syncline, or to what extent if any they have been modified by pressure from the Trinidad ranges on to the Archaean foreland. In the Cuyuni River, much of the gneiss east of Pap Island has a north-easterly foliation, but there are local disturbances. The fresh basic intrusives are not foliated ; but dykes of such rocks seem to have a strong tendency to orient themselves in the north-east to south-west quadrants. The most recent of these are of post-Kaieteurian age.

If the age of the Kaieteur sandstone be assumed to be at least as old as Siluro-Devonian (say equivalent to Voltaian or Table Mountain Sandstone), it would not appear that there has been much orogenic movement in the Guiana Shield since that time, although it has acted as a foreland against considerable forces from the Caribbean Sea. The lower part of the Amazon syncline trending slightly north of east contains Devonian rocks ; to the north of British Guiana the similar trend of the Trinidad ranges and of the Bartlett-Brownson Deep is worthy of note. The orientation of the volcanic arc of the Lesser Antilles is, however, from north to south, which is that of the Berbice syncline and the Essequibo " break ". It is possible that this volcanic island-arc may have originated as a tension-crack resulting from north-to-south compression of a big strain-ellipsoid in the Caribbean :—the compression responsible for the Trinidad ranges ; but it is much more likely that it lies on a thrust-plane intersecting the geoid at a low angle, like others described by Lake (1931*a* and 1931*b*). In that case the sole of the thrust would dip westwards, with under-riding toward the west and over-riding toward the east. The chord of the arc is paralleled, though not exactly aligned, with the north-to-south " Essequibo tectonic line ", which might well be an extension of the Antillean weakness. The rise of the block west of the Essequibo which brought the White Sand up at least 600 feet at Aranka, may well have been accompanied by movement along this line.

CONTINENTAL SLIDING AND LINKAGE WITH AFRICA

Du Toit (1937) has demonstrated the extraordinary correspondence of the southern and western portion of the African continent with the eastern portion of South America from Brazil to the Argentine. The similarity is apparent in tectonics, magmatics, lithology, stratigraphy, palaeontology, and even in coast-line. Whatever views may be held on the hypothesis of continental sliding, a comparison of the Guianas with the quasi-equivalent portions of West Africa must be attempted ; but owing to the lesser knowledge of the northern part of South

America, it is not quite so easy to compare the two regions north of the equator. However, du Toit has pointed out the following :—

> " The structural axis of the flat arch of Siluro-Devonian sandstones of West Africa runs west-south-west from about Tassili through Sierra Leone. If prolonged this axis would pass into the Guianas where the similar horizontal Roraima (Kaieteurian, D.W.B.) sandstone caps the crystallines and forms lofty territory running northwestwards into Venezuela."

He also connects :—

> " the Amazon syncline with its marine Silurian, Devonian and Carboniferous strata resting on crystallines and trending a little south of west " with the Voltaian beds of the Gold Coast " and the down-faulted strips trending southwestwards of marine Devonian and probably early Carboniferous between Accra and Sekondi ". He adds that " it is significant that the several diamondiferous areas in British Guiana, Sierra Leone and the Gold Coast fall on a nearly straight line ". Finally he makes the point that the " Alpine foldings of the Atlas ranges . . . correspond precisely with those of Trinidad and Venezuela which have an east to west strike, each involving . . . groups . . . all overturned toward their continental masses."

As du Toit points out (fig. 13, *Our Wandering Continents*), the reconstruction of the Gondwana continent shows a large triangular gap between the Guianas and Senegal (this reconstruction requires a rotation of South America through about 45°).

The gaps in our present knowledge of the Guianas are disconcerting, but some comparisons may be made.

(1) In the Gold Coast and in Sierra Leone the " grain " in the Basement Complex is sharply defined, and is oriented approximately south-south-west, say at 205°. In British Guiana it is by no means so uniformly or clearly presented (possibly on account of a greater wealth of later intrusive masses) ; but regional strikes of 240° and of 130° are not uncommon. The Amazon syncline with axis striking at (say) 260° registers quite well with the Gold Coast strike when the continental rotation of 45° required by the reconstruction is applied ; so does the foliation of 240° in British Guiana, but not that of about 130° in the North-West District of the latter Colony. However, this North-West District approaches more nearly to Trinidad and the Orinoco syncline, and as suggested earlier in this paper, the strikes may have been modified by the post-Cretaceous pressure :—the forces which drove the Trinidad ranges against this foreland.

(2) No fossils have ever been found in the Kaieteur sandstone, but on lithological grounds it is reasonable to correlate it with the Voltaian sandstones of West Africa, and these in turn with the Table Mountain Sandstone. On the other hand the

Kaieteurian might also well be correlated with the Tarquaian sandstone, a far older formation, but still not very heavily folded. The Tarquaian sandstone rests on a crystalline floor very similar to that of British Guiana, and lithologically has points of resemblance to the Witwatersrand Quartzites. It seems improbable, however, that the Kaieteurian is as old as the Witwatersrand ; and in the curiously erratic sizing and irregular grading of its pebbles it seems to have some Devonian affinities.

(3) Evidence points to the source of the alluvial diamonds in British Guiana being the Kaieteur sandstone. In Brazil some of the diamonds appear to come from a similar non-fossiliferous sandstone which in Paraná is regarded as a Devonian basal conglomerate, and elsewhere has been tentatively referred to the Carboniferous. In the Gold Coast the source of the diamonds is attributed to the Upper Birrimian (which includes the Kawere conglomerates and volcanic rocks), which is part of the pre-Tarquaian Basement, and whose members resemble the Volcanic Series in the Basement of British Guiana. But in South Africa diamonds have been found in the Witwatersrand Quartzites, evidently from a still older source. There is no evidence to rule out the possibility of the Kaieteur sandstone being Precambrian, and far older than the Voltaian or Paraná formations. The thin Itawah and Vamari shales apparently form a basal bed to the Kaieteurian.

The writer is of the opinion that in the African and South American continents there are two possible sources of diamonds, of which one is the well-known eclogite pipe formation. There seems also to be a suspicion that diamonds form a very sparse constituent of the ancient highly metamorphosed rocks which may at one period have been subjected to the conditions of the "paramorphic zone" postulated by du Toit. The diamond can in fact occur in any coarse psammitic sediment which happens to originate directly from, and be superimposed on, the crystalline basement, and is a bad mineral for correlation purposes, except in respect of its own particular characteristics. Its mere presence may only indicate the type of physical conditions to which the basement has been subjected.

An important mineralogical resemblance is provided by the recent discovery (du Toit, 1937) in the Gold Coast of rolled specimens of gorceixite, hitherto known only in Brazil. The abundance of the much commoner staurolite in the Volcanic Series of British Guiana has been noted, and is paralleled by staurolite-gravels near Saltpond in the Gold Coast. It would indicate that the same types of rocks have been subjected to similar processes in similar degree. Both countries again provide bauxite and manganese. The enrichment and concentration of such minerals are no doubt due mainly to climatic conditions and perhaps to biochemical processes ; but the raw materials are there, and are similar in each case. The modes of occurrence of the bauxite are not quite similar : in the Gold Coast it is found as a high-level capping by alteration of phyllites and andesitic rocks ; in British Guiana it is a low-level deposit whose provenance is not certain at present. If it has not arisen by alteration of the crystalline basement in situ, it might have been derived by solution of iron from the lateritic peneplain which descends gently toward the Berbice basin ; or perhaps by alteration of one of the large dolerite sills which are common in the Colony, and over which the White Sand sea may have transgressed.

(4) The lithological characters in the crystalline rocks of British Guiana and West Africa compare fairly well : the newer granites of both countries, and the Volcanic Series of each country in the upper parts of the Basement Complex. There are black manganiferous and carbonaceous shales and phyllites and bands of greywacke in both systems, and lavas of andesitic character. The volcanic agglomerates of the Kawere formation (Gold Coast) are paralleled in a striking fashion by the agglomerates and tuffs of the Volcanic Series of British Guiana. (The writer has at different times examined the rocks in both countries, but has not had the opportunity of making direct comparison between typical specimens.)—There can be no doubt as to the similarities between the respective crystalline basements, which in each case are succeeded unconformably by the sandstones already described. Comparison should also be made between the fresh gabbros of Guiana and a norite at Mona (Kuribrong River), and the norite of Sierra Leone and the dolerites of the Gold Coast. The post-Kaieteurian dolerites of British Guiana have never been dated, but they could well correspond to the Karroo intrusions in South Africa. In only one case is the writer aware of the occurrence of olivine in a Guiana dolerite ; those examined show the usual pyroxenes in a matrix near to labradorite.

(5) The criteria demanded by du Toit for a continental fault-line coast are not absent in West Africa and in British Guiana. In drawing the parallel between South Africa and Brazil he has pointed out the arrangement in the latter country where an escarpment faces the ocean " behind which the Parana, Uruguay, and São Francisco Rivers take their rise and

flow for extraordinary distances parallel to the coast, developing magnificent waterfalls and rapids before reaching the sea ". This would apply to the upper portion of the Mazaruni. The criteria that he gives are these :—

> " One will find an escarpment either close to or away back from the sea, while from the resulting plateau-edge the larger drainages will be directed inland, to reach the ocean only some distance away. . . . To do that the rivers may have had to pass through gaps in the escarpment or take a circuitous route to avoid the latter, and have commonly developed cataracts. . . . The following elements are then normally represented : the interior mature plateau with inland slope, the escarpment, the moderately or else considerably dissected coastal zone, the narrow continental shelf, and the steep slope to the ocean deep beyond."

Extending du Toit's comparison farther to the north and west for each of the two continents, we find in the Gold Coast the escarpment set back some 300 km. from the coast, and a " backward " drainage of the Niger and Senegal rivers. There is also direct evidence for a fault-line coast. In British Guiana as in Brazil the conditions are also represented. There is the plateau of the Pakaraimas with inland slope (the Cotinga, Ireng, Kukenaam, and part of the Mazaruni river draining the south-west quadrant) ; the escarpment of the Kaieteur sandstone set well back from the sea (through head-stream erosion, and marine erosion in White Sand times) ; the considerably dissected coastal zone, in this case the intermediate peneplane which is at a fairly low level. The continental shelf is not narrow, but quite a small elevation would make it so, and it has a very steep slope to the oceanic depths from its edge. The so-called " Essequibo break " has already been mentioned, and the coincidence of its northward projection with the western margin of a deep ocean basin. It has already been suggested that the country along the west of the lower Essequibo formed a pre-White Sand coast line, and that this indeed was a fault-line coast.

Finally, there is the long course of the Cuyuni and Mazaruni rivers parallel to the coast, and the extraordinary spiral course of the Upper Mazaruni with its cataracts, starting with an inland drainage, and—" taking a circuitous route to avoid the escarpment ". Now it will be noticed that du Toit's criteria apply to the block west of the Essequibo river, but definitely not to the area between the Essequibo and the Corentyne ; they are missing in the region of the Berbice downwarp where the rivers run northward to the sea, where there is no high plateau in the interior, and from which region all the Kaieteur formation has disappeared. Three small outliers of the latter are reported from the lower portion of the Corentyne river, but on the east bank, and there is a larger one (Tafelberg) roughly in the centre of Surinam. The rivers of the latter country between the Corentyne on its western, and the Marowijne on its eastern border have a general northward or north-easterly drainage to the sea.

If a subsidence of (say) 600 feet be allowed for the transgression of the White Sand sea, the headstreams for the drainage of the interplateau region between the Essequibo and the Corentyne would come extremely close to the Amazon system. In fact the suspicion now arises that at one time the Amazon may have had a northern mouth, draining out through the Berbice synclinal with its supposed 3,000 feet depth, or more, of unconsolidated sediments. The brown and yellow sand lenticles at the base of the White Sand are known to be of fluviatile origin. Harrison indicated the probability of a large old river channel existing to the north of Berbice. Grantham and Paton, already quoted, suggest that the Ireng and Takatu which now flow into the Amazon, formerly flowed into the Berbice. Passarge (as cited) mentions the possibility of the Takatu having been captured from the Essequibo headwaters. Du Toit remarks that there is a strong suggestion that the Amazon formerly discharged westwards, but that its flow became reversed through the Andean uplifts. The extremely low elevation of the greater part of the Amazon basin above sea-level has been noticed by several authorities, and has been given (Church, 1901) as only 36 feet at the mouth of the Javary, over 2,000 miles from the Atlantic. The depth of the river is also considerable. Sherlock (1934) refers to a great fossil delta far inland, that "faces the wrong way" on the Amazon river: this supports du Toit's contention as to the reversal of flow. If the hypothesis of a sometime northerly discharge of at anyrate part of the waters from the Amazon system be acceptable—and the work of the recent Boundary Commission should go a long way to settle the question—it could be equally valid whichever way the water in the main Amazon channel were flowing. It is worth while trying to visualize what would happen if an Andean reversal of a formerly westward-flowing Amazon took place;—and the Amazon depression appears to have existed for a very long time. There would have been relatively high ground to north and south of the river; and the first consequence of the rising of the Cordilleran dam and of the easterly tilt would have been the formation of large, perhaps very large, lakes. Such lakes must have found natural spillways toward the edges of the continent until the reversal of the Amazon was fully established, and any breaches in the Kaieteurian rocks to the north, such as might be caused by the sinking of fault-blocks or the downwarping of synclinals would surely serve as channels initiating the northerly drainages east of the Essequibo. Not less instructive is a mental picture of what would be the distribution of the waters at the present day if the northern part of the continent were to sink so little as 500 feet. This would bring the sea right up to the foot of Kaieteur and the Pakaraimas, and practically reproduce the White Sand conditions.

VIII. CONCLUSIONS

The studies of the geomorphology seem to show that in British Guiana there is a marked difference between the blocks west and east of the Essequibo, at least north of, say, Lat. 5° N. A break or fracture along the Archaean floor of the Lower Essequibo is postulated, involving both downward and upward movements along this line, in addition to the downwarp of the Berbice axis. It is also suggested that at some time the Essequibo–Berbice–Corentyne region may have provided a gap in the Kaieteurian plateau of sandstones found west of the Essequibo and east of the Corentyne ; and that this gap may have served as a means of draining a part of the Amazon system before the present divide was established. The possibility of downfaulted Kaieteurian sandstones lying deep under the Berbice alluvium has not been overlooked.

On the question of continental sliding, the writer retains an open mind, and there is much more work to be done. The downfaulted nature of the coast-line in the Gold Coast is accepted ; but it would appear that in British Guiana such marginal faults would have to be referred to the edge of the continental shelf, and to an ancient coast formerly existing on the left bank of the lower Essequibo. On the balance, the writer would prefer to assign the age of the Kaieteurian sandstone to the Devonian ; but if one accepts the idea of continental linkage here, there is the difficulty arising from the two sandstone systems, Voltaian with downfaulted coastal Devonian, and Tarquaian in the Gold Coast, to be connected with (so far as is known) only one Kaieteurian in the Guianas. Harder, however, has suggested that it may have Triassic or Cretaceous affinities through its similarity to beds of known age in Brazil.

The parallel between the crystalline basements in both countries appears to be particularly close, and the Kawere can be matched by the Guiana Volcanic series. Du Toit's fault-line coast criteria apply to the area west of the Essequibo.

Although the similarity between West Africa and the Guianas is at present less certain, and information less complete, than that provided by the more southerly portions of Africa and South America, yet there is a good degree of correspondence ; but this is better marked in the case of the crystalline basements.

The Amazon basin very nearly cuts South America in half from east to west, and constitutes an erosion and drainage system of such tremendous size that problems of geomorphology in the Guianas cannot well be studied without reference to its past history. The country at the back of the Guianas is not very well known or mapped, and it seems worth while to formulate a few hypotheses which, however speculative, may be tested as exploration progresses.

IX. ACKNOWLEDGMENTS

The attached bibliography is not complete, but it includes those works referred to in the text ; and the writer has also drawn conclusions from some reports of his own which are as yet unpublished. The original work on, and discoveries of, bauxite in British Guiana by the late Sir J. B. Harrison were first published in the *Geological Magazine*. Due acknowledgment is also made to the fellow-geologists whose ideas and discussions have stimulated the foregoing notes. It is hoped that the divorcing of certain unavoidable quotations from their contexts has not in any way misrepresented their authors' views. The hydrographic notes are based on British Admiralty chart No. 1801, and on the Dutch charts of this coast, which I was able to study, through the kindness of officers of the Royal Dutch Mail Line.

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The Genus *Mentzelia* Quenstedt, and its affinities to other members of the Subfamily Martiniinæ Waagen.

By James Archibald Douglas, Professor of Geology,
Oxford University.

WHILE studying certain *Martinia*-like brachiopod shells from the Permian of Iran, I have been struck by the apparent uncertainty that exists among many authors as to the relationship between the various genera represented in the Spiriferid subfamily Martiniinae of Waagen, and the following note is intended to draw attention to some of the anomalies of nomenclature and classification.

In 1894 James Hall in his Description of the Brachiopods of the State of New York (1894, pp. 12–40), divided the family Spiriferidae into six groups, those shells belonging to the subfamily of Martiniinae being included in the group Glabrati, an emendation of the division Glabratae previously suggested by Phillips in 1836.

This group he subdivides into :—

(1) Aseptati. Shells in which dental lamellae and septa are wanting. Exemplified by *Martinia*, McCoy, 1844.

(2) Septati. Shells in which dental plates or septa are well developed.

These include :—

(*a*) *Martiniopsis* Waagen, 1883. Type, *Martiniopsis inflata* Waagen, from the Upper *Productus*-limestone of the Salt Range, with strong dental lamellae but no median septum.

(*b*) " Gen. Nov." Tschernyschew, 1889. Type, *Martinia semiplana* Waagen, with dental lamellae scarcely developed, but with a prominent median septum.

(*c*) *Mentzelia* Quenstedt, 1871. Type *Spirifer medianus* Quenstedt, from the Muschelkalk of Silesia, with median septum and dental lamellae.

He states, however, that it seems very doubtful if forms included in (*b*) and (*c*) should be separated, and certainly the distinction as he gives it appears to be merely one of degree.

Later (1894, p. 40) he includes both *M. semiplana* Waagen and *M. corculum* Kutorga under the genus *Mentzelia*, although, by the use of brackets, admitting that they are extra-limital species.

Waagen, however (1882, p. 537), in his original description of *M. semiplana*, which he includes in the group of *Martinia* *corculum*, states: "Of the internal characters of this species nothing has been observed." In 1889, Tschernyschew (p. 369) proved the existence of a large median septum in the ventral valve of Kutorga's type of *M. corculum*, but stated that it lacked dental plates. Yet in 1902 (p. 564), he still records it as a *Martinia*, together with another form from the *Schwagerina*-horizon of the Urals, which he identifies with Waagen's *Martinia semiplana*, also possessing a large median septum extending from the apex of the ventral valve for the third part of its length. It is clear, therefore, that neither of these species is a true *Martinia*, but it is still doubtful if *M. semiplana* Tschern. is identical with *M. semiplana* of Waagen.

Further confusion arises from the fact that Rothpletz (1892, p. 80) identifies, although with some hesitation, his species *Martinia nucula* with *Martinia semiplana* Tschernyschew from the Urals. His reason for doing so is anything but clear, for he records the presence of two dental plates in the ventral valve but no median septum; features characteristic of *Martiniopsis*.

On the other hand the internal characters of Quenstedt's little-known genus *Mentzelia* (1871, p. 522) appear to be quite distinctive.

Waagen expresses the opinion (1882, p. 525) that *Mentzelia* appears to be most nearly related to his genus *Martiniopsis* but is distinguished by the development of a large median septum in the ventral valve and by the reduced size of the dental plates. By the study of serial sections of a number of shells from the Permian of Iran, where they are associated with *Linoproductus lineatus* (Waagen) and species of *Spirigerella* and *Spirifer*, it can now be shown that the genus *Mentzelia* is in fact represented in pre-Triassic rocks.

During the course of this investigation it became apparent that many authors have frequently established new species and assigned them to one or other of the four genera of the MARTINIINAE, by long descriptions of external shape and relatively unimportant details of measurements while omitting all reference to internal characters or stating that these were unknown to them.

It cannot, therefore, be too strongly emphasized that such a practice is valueless, for until the internal structure of these brachiopods has been studied no reliance can be placed on generic identifications, and even members of different families may be confused when owing to poor preservation the exact nature of the peduncle-opening is not clearly decipherable.

An instance of this was afforded by a number of *Martinia*-like shells collected from one horizon and sent to me for identification. These all bore a strong superficial resemblance, differences of size and shape being no greater than could be explained by variation within the limits of an individual species.

Serial sections of a number of these, taken at random, showed, however, in an unmistakable manner that not only were two genera present but actually two distinct Families; the SPIRIFERIDAE (subfamily MARTINIINAE) and the ATHYRIDAE.

The first, represented by the new species of *Mentzelia* described below was found to possess a strong median septum in the pedicle-valve and long well-developed dental lamellae, while the second was characterized by the extreme development of a large crural process in the brachial valve with a corresponding deep and narrow pedicle cavity entirely devoid of a median septum, a type of hinge-structure found in the Athyrid genus *Spirigerella* of Waagen, which James Hall has suggested is, at least in part, closely related to *Seminula* of McCoy. Without a knowledge of these internal characters both sets of shells might have been recorded as *Martinia* sp. for illustrations of species of this genus could be selected from the works of several authors, from which they are externally indistinguishable.

Family SPIRIFERIDAE, King.
Subfamily MARTINIINAE, Waagen.
Genus *Mentzelia*, Quenstedt, 1871.

Mentzelia persica sp. nov.
(Text-figs. 1, 1*a*, 2, 3*a*, 3*b*, 3*c*)

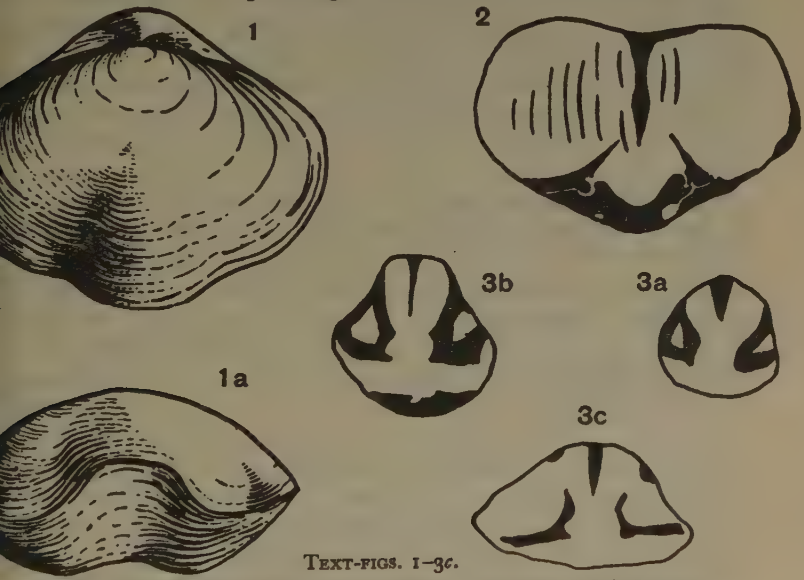
Description.—Shell externally resembling that of a *Martinia.* Outline subcircular to transversely oval. Dimensions of holotype: length 39 mm., width 48 mm., thickness 24 mm.

Surface smooth with occasional concentric growth-lines, the shell-substance being fibrous and impunctate.

Valves moderately inflated, subequally convex, non-plicated but with a prominent median fold in the brachial valve and a corresponding sulcus in the pedicle valve. This fold begins about half-way down the valve, and the young shell has only a slightly waved frontal margin.

The hinge line is shorter than the maximum width of the shell, and has rounded cardinal extremities.

The umbo of the pedicle valve is incurved over the hinge-line and almost completely conceals the delthyrium. The area is small and indistinctly marked off from the rest of the shell. The chief diagnostic characters of the shell, however, are not disclosed until the internal skeleton is examined by means of serial sections. The pedicle valve is then found to be provided with a strong median septum extending about two-thirds of its length and with stout dental lamellae supporting small teeth which fit into corresponding sockets in the brachial valve.



TEXT-FIGS. 1–3*c*.

1. Dorsal view of holotype, partly restored. Reg. No. A.I.O.C. 150.
1*a*. Frontal view of holotype.
2. Transverse section of holotype, showing median vertical septum in pedicle valve, and dental lamellae supporting teeth.
3*a*, 3*b*, 3*c*. Three transverse sections through a paratype.

All originals in the University Museum, Oxford.

The latter is devoid of a cardinal process and has no median septum.

The spiralia when preserved appear to be thin, somewhat loosely coiled and directed towards the lateral margins, occupying the greater part of the interior of the shell.

Locality and Horizon.—Qashgai Sarhad, Iran. Permian.

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CORRESPONDENCE

THE MAPPING OF HEAD DEPOSITS

SIR,—The authors of the paper entitled "The Mapping of Head Deposits", published in the last issue of the *Geological Magazine*, are indebted to Dr. F. J. North for calling their attention to an omission from the Historical section of references to papers by Strangways and Buckland. These were both read in 1819 and published in *Trans. Geol. Soc.*, First Ser., vol. v, 1821.

Both of these authors use the terms Diluvium and Alluvium, and give definitions. Mantell, referred to in the Head paper as being the first to give a scientific description of "head" deposits, quoted, to some extent, from Buckland, who had previously quoted from Strangways.

H. G. DINES.

GEOLOGICAL SURVEY AND MUSEUM,
LONDON, S.W. 7
1st July, 1940.

REVIEWS

CONTRIBUTIONS TO THE GEOGRAPHY OF EGYPT. By JOHN BALL. Ministry of Finance. Survey and Mines Department. Cairo, 1939. Price 10*s*. 6*d*.

Well over half of this important memoir is devoted to geology. Most of the rest deals with the solid matter transported by the Nile and with the characters and age of the resulting alluvium, a subject intimately concerning geologists.

Chapter 2, "Egypt in past geological ages," comprises in twenty-five pages the most up-to-date account yet written of the geology of Egypt and is a masterpiece of compression. Chapter 3 offers in another twenty-five pages a critical account of the Nile terraces and raised beaches, and the light they throw on Palaeolithic man and such questions as the age of the Isthmus of Suez. Chapter 4 is the most original and perhaps the most important contribution in the book. One of the major problems confronting students of the Nile Valley Pleistocene deposits has been the sudden influx of vast quantities of silt in the Sebilian or Upper Palaeolithic period. It is piled up to 100 feet above the present flood-plain at Wadi Halfa and chokes the mouths of the dry tributary wadies. Its surface sinks gradually northwards until it disappears below modern alluvium near Nag Hamadi. To explain this Dr. Ball postulates a vast Lake Sudd over the Central Sudan in Pleistocene times, with a length of over 1,000 kilometres, and stretching from near Shambe to Khartoum. Into this flowed the Blue and White Niles and deposited their silt. At the same time the Egyptian Nile was fed only by the Atbara and some small tributaries, one of which drained from the hills near the Shabluka Gorge, the water parting between the Atbara-Lower Nile and Lake Sudd. At the beginning of Sebilian times this tributary cut back across the Shabluka divide and tapped the lake, which immediately deepened the outlet, forming the present gorge, and poured its reservoir of silt into the Lower Nile Valley.

Chapter 8, which occupies over one-third of the book, deals with the complicated history of the Faiyum and Lake Moeris. The ancient Egyptological and medieval evidence, the arguments and hypotheses of the early investigators of the modern period, and the polemics of the last few years are sifted by a master hand and set out in a style and with a lucidity which convert an awkward mass of material, full of contradictions, into a fascinating and convincing story. Dr. Ball comes down on the side of the Geological Survey in interpreting the Gisr el Hadid as a beach of the Ptolemaic Lake Moeris described by Herodotus; and to the same period, at least in part, he ascribes the Edwa Bank. But he does not refer to some criticisms which have been brought against the Survey's interpretation (*Bull. de l'Inst. d'Egypte*, vol. xix, 1937).

Of four excellent folding maps one, with contours at 10 metre intervals and layer colouring, is the best map yet published of the Faiyum and Wadi Rayan, and is an indispensable adjunct to Chapter 8. There are also excellent geological and relief maps of Egypt with Sinai.

W. J. A.

GEOMORPHOLOGY: AN INTRODUCTION TO THE STUDY OF LANDSCAPES. By A. K. LOBECK. pp. xii + 731. London: McGraw-Hill Publishing Co., Ltd., 1939. Price 25*s*.

Most American textbooks of geology and kindred subjects are profusely illustrated. In some of them there is occasionally no more than a river of text meandering down the page, an arrangement that does not facilitate reading. Professor Lobeck's book is the most fully illustrated of them all, but he avoids this pitfall. The illustrations actually form two-thirds of the whole, but they never break a line of type. Sometimes a single figure occupies a whole page ; sometimes several are grouped together upon the page opposite to the text that deals with them ; sometimes one is on the same page as the text, but it occupies the full width and there are never any short lines of type at its sides. The illustrations include photographs, diagrams, and maps ; and they are systematically arranged. Most of the photographs are placed at the beginning of the chapter that they illustrate ; the diagrams are in the body of the chapter as near as possible to the appropriate text ; the maps are at the end of the chapter.

The selection of the photographs and maps and the designing of the diagrams must have cost the author at least as much trouble as the writing of the text. His readers will certainly appreciate the result. He recommends the student to give as much time to the study of the illustrations, especially the diagrams, as he does to reading the text. The advice is hardly needed. The diagrams are so attractive, so clear and self-explanatory, that most students will do so of their own accord.

Those who already know something of the subject will undoubtedly find much to interest them. The beginner may fear that so large a book must be beyond him, but it is not so. The alarming size of the volume is due chiefly to the illustrations. If these do not waken the interest of the beginner he should try classics or modern languages or some other man-made subject. The study of nature is not for him.

The book, in short, is an admirable exposition of its subject, much of its value lying in the remarkably extensive series of well-designed diagrams which accompany the text.

P. L.

GEOLOGICAL MAGAZINE

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The Geology of British Oilfields

I. The Geology of the Assam–Arakan Oil Region (India and Burma)[1]

By H. M. SALE and P. EVANS

I. INTRODUCTION

THE oil regions of India lie in the north-west and in the east, within broad strips of Tertiary rocks stretching in a general southerly or south-westerly direction from the Himalayas to the sea. On the eastern side of India the main Tertiary outcrop runs from the head of the Assam Valley south-westwards through part of the Central Assam Range into the Surma Valley and thence southwards to the Bay of Bengal at Chittagong, whence the Tertiary beds continue along the Arakan Coast of Burma. This strip forms one geological province, distinct both from the better-known Tertiary development of western India and from the Tertiaries of the Chindwin–Irrawaddy Valley of Burma. This Assam–Arakan region includes parts of the provinces of Assam and Bengal and part of the western coast of Burma: although Burma is now separated from India, it is convenient to consider the Assam–Arakan oil-belt as a whole, without regard to political divisions.

II. HISTORICAL REVIEW

Progress of Geological Investigation.

References to the geology of Assam are to be found in the writings of several early observers but the first systematic work was carried out by H. B. Medlicott (1869) and F. R. Mallet (1876) of the Geological Survey of India. Mallet's work laid the foundations of the Tertiary geology of Upper Assam, but interest was focussed on the coal occurring on the borders of the Brahmaputra Valley and in the Central Assam Range, and little attention was paid to other parts of the region. In 1912

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[1] Contributed by permission of the Burmah Oil Company, Ltd.

E. H. Pascoe included in his memoir on the oilfields of Burma a brief description of the Arakan part of the region, and in 1914 he summarized what was known of the Tertiaries and of the occurrences of petroleum in Assam and Bengal. A few years earlier the geological staff of the Burmah Oil Company had begun an examination of the Assam–Arakan region, and this survey has been continued with increasing detail until all the more accessible (and many of the less accessible) parts of the Tertiary outcrop have been studied. For shorter periods the geologists of the Indo-Burma Petroleum Company and the Whitehall Petroleum Corporation have worked in Assam and Arakan. During this time the pre-Tertiary rocks and some of the Lower Tertiary rocks of Assam have been examined by the Geological Survey of India, but the systematic survey which has recently been resumed has not yet reached the parts of the region where indications of oil occur.

The Tertiary rocks, in which all the oil of Assam–Arakan occurs, attain a very great thickness, and are remarkable for the extreme scarcity of fossils throughout most of the region. Almost the whole of the Tertiary outcrop is covered with thick jungle, and the investigation of the stratigraphy of a somewhat monotonous and almost unfossiliferous succession of impure clays, shales, and sandstones has been a slow and difficult task, but the field-work of the past twenty-five years, supplemented by micro-petrological evidence, has led to the establishment of a local classification in Assam which has gradually been extended to cover the 800-mile outcrop of the Tertiaries from the Himalayas to the Arakan Coast. The classification evolved is necessarily based on lithology and the divisions are lithological ; to what extent they depart from time-divisions is unknown. Local names, some established by Mallet and some newly applied, have been given to the lithological divisions, and the palaeontological evidence, though restricted, is sufficient to enable some of these divisions to be placed roughly in the standard time scale. Two of the unconformities have been found to be widespread and their recognition has helped considerably in the correlation of different parts of the region. The most important of the breaks separates the Upper and Lower Tertiaries.

Methods of Geological Investigation in Assam–Arakan.

A large part of the extensive alluvial plains of Assam and Arakan has been cleared for the cultivation of rice or tea, and although the clearing has extended to a few of the lowest hills, the geologist working in this region is concerned mainly with the less accessible jungle-covered hills, which, with their heavy rainfall, lack of paths, thick coating of soil, and almost impenetrable undergrowth, present many hindrances to geological investigations. Conditions during the torrential rains of the monsoon season make mapping so difficult that it is wise to curtail the field season to the driest months of the year, and as travel is almost invariably slow, the progress of geological work is much less rapid than in the more open parts of India.

With the high relief of much of the country, many of the hillside streams have cut down sufficiently to give fairly good exposures, although the softer rocks tend to be concealed by boulders, but outside the stream beds there are in most of the Tertiary area but few chances of seeing the rocks. The thick coating of soil conceals the outcrops and opportunities for following horizons from one stream to another are very limited : mapping thus consists mainly of a series of stream traverses, and in detailed work every stream must be searched. Where the dips are fairly high, the harder rocks form more or less regular ridges, and the softer ones permit the development of a series of strike valleys ; this type of evidence is of much assistance in reconnaissance work, but is insufficient to define, except very roughly, the position of boundaries needed for detailed mapping.

The lack of variety in the lithology and the absence of help from palaeontology make it difficult to correlate isolated sections, but fortunately study of the petrology of the sediments has revealed differences in the "heavy mineral" content that can be used to aid correlation. The examination of many thousands of slides of heavy mineral residues has shown that although the variations of mineral suites can be of great assistance, very detailed work is required. The succession of mineral suites is in a general way one of increasing complexity. In the older Tertiaries the total heavy mineral content is small and few minerals are present—mostly the more resistant ones. Staurolite is all but absent from the Lower Tertiaries, but is the first new mineral to appear above the break which separates the Upper and Lower Tertiaries. At a higher horizon, epidote, previously present in small quantities, becomes abundant, and several other minerals previously but rarely present become rather more persistent although never abundant ; in still higher beds hornblende becomes more abundant. The total proportion of heavy minerals is much greater in these higher horizons and the mineral suite includes many more species: epidote, garnet, and hornblende are the dominant non-opaque minerals in all but the highest divisions of the Upper Tertiaries, and others of importance in correlation are andalusite, chloritoid, enstatite, hypersthene, kyanite, sillimanite, staurolite, titanite, and zoisite; rutile, tourmaline, zircon, and the opaque minerals are of less diagnostic value.

Although there are these broadly recognizable mineral zones it is not possible to pick out a slide at random and from a count of the minerals to be sure of placing it in the proper stratigraphical position. There is much variation from one bed to another and although, for example, a sample from below the range characterized by epidote would be unlikely to contain epidote in quantity, it is quite common to find samples within this range that contain comparatively little of the characteristic mineral. The method which has been evolved to make use of the petrological evidence depends on the collection of samples at close intervals from a long range of beds, and the accurate determination of the proportions of all non-opaque minerals. The variations in " frequency " of about twenty minerals are plotted on a range table, using a scale which is approximately logarithmic. Comparison of range tables from different areas has shown that the horizons at which the epidote, hornblende, and other minerals first appear in quantity are not constant throughout the Assam–Arakan region, but it is remarkable that the sequence of characteristic mineral suites is very similar wherever samples have been taken throughout the 600-mile outcrop between the head of the Assam Valley and Akyab District.

In addition to the geological mapping and the application of sedimentary petrology, there has been extensive geophysical work including torsion-balance, gravimeter, seismic, and electrical surveys. The torsion balance has been successfully used in tracing faults beneath the alluvium.

Development of the Oil Industry.

Early Records.—Although the indigenous oil industry of the Irrawaddy Valley of Burma is known to be very ancient—there were over 500 wells at Yenangyaung in the latter part of the eighteenth century, and Pascoe writes of an unconfirmed Chinese record of the thirteenth century—little is known of the origin of the industry on the Arakan Coast. There is a tradition that the *Twinsayos* (who for many years have been workers on the Yenangyaung oilfield of Burma) were brought over from Arakan by one of the Burmese kings, and it seems possible that the Arakan workings are the older. It is recorded that the oil-wells of Arakan were worked before the annexation in 1826, a specimen of oil from Ramree was sent to the Asiatic Society of Bengal in 1833, and there was an extensive Arakanese industry at the time of Mallet's visit to Ramree and Cheduba in 1878. In 1778 Pogson visited and described the seepage of gas which is the source of the perpetual fire in the Hindu temple of Chandranath at Sitakund near Chittagong. This shrine was later visited by Hooker. At the northern end of the Assam–Arakan oil-belt, in Assam, there is no record of any indigenous oil industry. Most of the oil-shows near the head of the Assam Valley lie in jungle-covered hill country that was almost completely unknown to Europeans a little more than a century ago. The first explorer to visit any of the Assam seepages was probably Wilcox, who in 1825 went up the Dihing[1] Valley and over the watershed to the head-waters of the Irrawaddy. During the next twenty years other oil-shows were recorded in the hills on the south-eastern side of the Brahmaputra Valley.

Later Developments.—In 1865 H. B. Medlicott, during a visit to the coal outcrops of Upper Assam, found many oil-shows and on his recommendation an attempt was made to develop the oil of Assam. Drilling started in 1866, only a few years after the completion of the first oil-well in the U.S.A.; four shallow wells near Jaipur (south-west of Digboi) were unsuccessful but a small amount of oil was obtained from wells on the Makum–Namdang structure near Margherita. A brief account of the results of drilling was given by T. W. Hughes in the Records of the Geological Survey of India for 1874. The absence of transport facilities discouraged further attempts at development and nothing more was done until a railway had been made from the Brahmaputra to the coalfields near Margherita. In 1883 the Assam Railways and Trading Company began drilling on the Makum–Namdang structure but the yields were again disappointing. Meanwhile attention had been drawn to oil seepages near Digboi and the same company started drilling in this area in 1889. Many difficulties were encountered and only small amounts of oil were obtained. To deal with these, and the small production from Makum–Namdang, a refinery was built at Margherita. Later the Assam

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[1] The Brahmaputra tributary flowing past Margherita.

Oil Company was formed and the poor results on the Makum–Namdang structure led to concentration of drilling on the Digboi field, and the removal of the refinery to Digboi. Production continued to be small and it was not until after the Burmah Oil Company had acquired an interest in the Assam Oil Company that development on a large scale was undertaken. Between 1922 and 1930 production at Digboi was increased from about 350 barrels per day to the present figure of about 4,500.

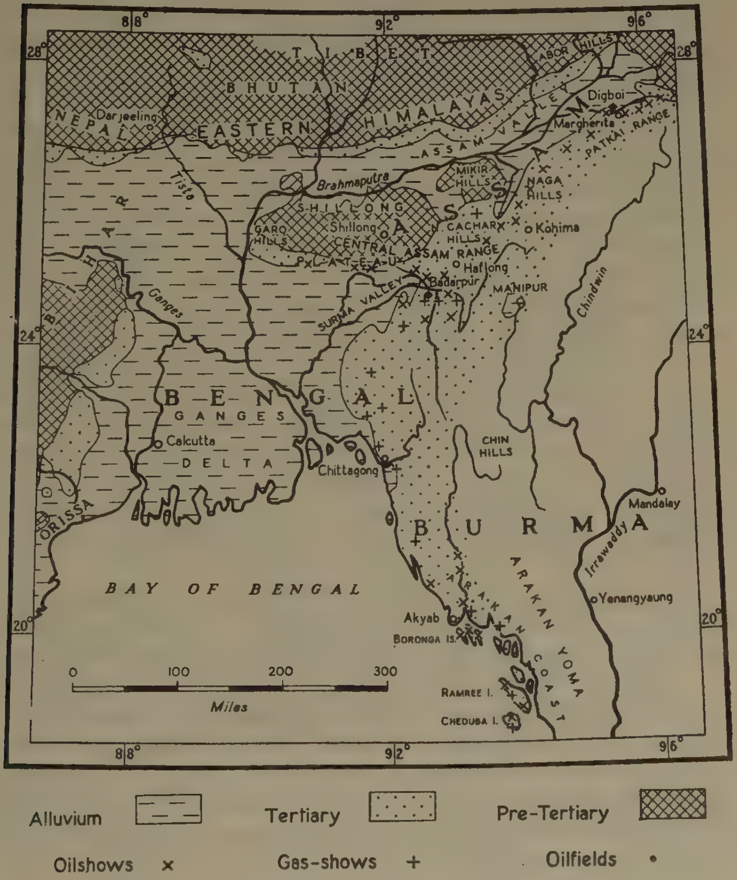
In the Surma Valley oil was proved in small quantities on the Badarpur Tea Garden in 1915 and the Badarpur field was developed by the Burmah Oil Company. It was soon found that the field was a very small one and it became exhausted after eighteen years' working.

In Arakan, although oil has been obtained from shallow wells for very many years, no important oilfield has been found. At the time of Mallet's visit in 1878 drilling operations were in progress in the Boronga and Ramree Islands but when prolonged attempts to find oil in remunerative quantities failed, the Boronga and Australian Oil Companies ceased operation. Pascoe's writing of thirty years ago indicates that in the Boronga Islands about 50 shallow wells had been drilled ; in Ramree Island the number was probably about 500 and in Cheduba Island possibly between 50 and 100 wells. Many wells were less than 100 feet deep (some very much less) and productions were very small. One well was recorded as giving thirty barrels in the first day, but this was an exception and Pascoe mentioned that in Ramree the average daily yield per producing well was probably less than two gallons. Production from the wells on the Eastern Boronga Island continued until a few years ago, and the Minbyin field on Ramree is still working in a small way. In some localities where oil has been found the Arakanese operators apply a modified system of percussion-drilling for the sake of a few bottles of oil a day. The oil is burnt without refining.

Despite the amount of work and money expended in prospecting throughout the Assam–Arakan region, the only oilfields of importance which have been found are Digboi and Badarpur. The Assam Oil Company have drilled tests in several areas in Upper Assam ; the Burmah Oil Company have drilled further south in the Assam Valley, in the Surma Valley, and near Chittagong ; Turner, Morrison and Company, the Indo-Burma Petroleum Company, the Whitehall Petroleum Corporation, and the Assam-Burma Company have also drilled in the Assam–Arakan region.

III. STRATIGRAPHY

The Tertiary belt of Assam–Arakan is limited on the north and north-west by much older rocks, on the south-west by the Bay of Bengal, and on the east by the little-known country of the Patkai Range, the Chin Hills, and the Arakan Yomas. In addition to the main outcrop running from the head of the Assam Valley to the Arakan Coast, there is a narrow strip of Tertiaries fringing the Eastern Himalayas[1]; there are also scattered outcrops of Tertiary rocks on the western side of the Ganges Delta.



TEXT-FIG. 1.—Map of the Assam–Arakan Oil Region.

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[1] Or Assam Himalaya.

The Older Rocks.

The metamorphic rocks of the Eastern Himalayas include schists, coloured slates, phyllites, dolomites, brecciated limestones, and quartzites. Further east, hornblende-gneiss and garnetiferous-gneiss are found in the hills at the head of the Assam Valley. The Shillong Plateau and Mikir Hills are largely made up of gneiss with intrusions of granite, peridotite, and dolerite. Overlying the gneiss is the Shillong Series of quartzites, sandstones, conglomerates, slates, and schists.

Rocks of the Gondwana System have been found along the foot-hills of the Eastern Himalayas; they include quartzites, shales, and carbonaceous shales, but the coal seams which occur are of no commercial value on account of the intense crushing. In the Abor country, towards the eastern end of the Eastern Himalayas, the Gondwana rocks are associated with basaltic lavas and tuffs: no Gondwanas are known further east. Recently the presence of Gondwanas has been established on the western fringe of the Garo Hills.

In the southern part of the Shillong Plateau there are andesitic traps, probably of Jurassic age, overlain by Cretaceous beds. These Cretaceous rocks rest on a very irregular surface of gneiss, trap, etc., and are mainly sandstones, often with an irregular basal conglomerate. Fossils suggestive of an Upper Senonian age, and having affinities with those of the Cretaceous of Madras, Madagascar, and Natal have been found near Cherrapunji.

Little is known of the geology of the ranges separating Assam and Bengal from the Irrawaddy Valley of Burma: although in the north-east Tertiary rocks extend across the watershed into the Chindwin Valley, further south the hills are composed of rocks of uncertain age showing varying degrees of metamorphism; they include schists, slates, splintery shales, and limestones and are traversed by serpentine and by quartz veins. Cretaceous fossils have been found on the Burma side of the watershed, and towards the southern end of the Arakan Yomas the Trias may be represented.

Tertiary Rocks—Classification.

The subdivisions of the Tertiaries of the Assam–Arakan region[1] are shown in the accompanying table. It will be seen that for the Upper Tertiaries the classification applies to the whole area examined ; in the Lower Tertiaries there are differences between the three sections given in the table. The most important difference is in the lowest division of the Tertiaries, which, in a comparatively small tract of country forming the southern and eastern part of the Shillong Plateau, exhibits a calcareous facies not found in the greater part of the outcrop. The dividing line between the two facies of the Lower Tertiaries of the Shillong Plateau and North Cachar Hills is

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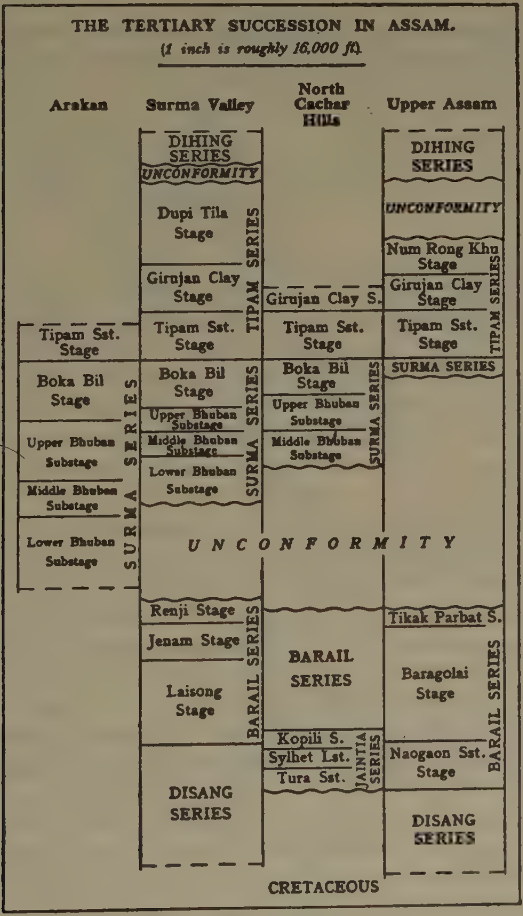
[1] The Tertiary stratigraphy of the north-west India and Burma regions has a fairly large literature, but very little has been written about the Tertiary stratigraphy of Assam and Arakan, and there is no readily accessible detailed account; it has been thought desirable to include a fuller summary of the stratigraphy than would otherwise have been necessary.



THE TERTIARY SUCCESSION IN ASSAM.
(1 inch is roughly 16,000 ft.)

also the dividing line between two types of structure, and it may be surmised that two different developments of the Lower Tertiaries have been brought into much closer proximity by overthrust faulting.

Lower Tertiaries—North-western Type.

It will be convenient to deal first with the Lower Tertiaries of the area fringing the Shillong Plateau. They have been divided as follows :—

Barail Series.

Jaintia Series	Kopili Alternations Stage. Sylhet Limestone Stage. Tura Sandstone Stage.

Jaintia Series.—The lowest Tertiary beds known in the western part of Assam are some almost unfossiliferous beds which at one time were thought to be Cretaceous ; these have been termed the Tura Stage and include the Cherra Sandstone. The thickness of the stage is very variable, but is never more than a few hundred feet. In the Tura Stage are arenaceous rocks of several different types with smaller thicknesses of other shallow-water beds ; thin coal seams are common, and in the Mikir Hills and locally in the Shillong Plateau the lowest beds are china-clays giving evidence of the early Eocene land surface.

The overlying Sylhet Limestone Stage includes several hundred feet of foraminiferal limestones associated with thin shales and sandstones. There is much lateral variation, and in general the stage becomes thinner and less calcareous in a north-westerly direction. In contrast to most of the Assam rocks the Sylhet Limestone is very fossiliferous, containing a Middle Eocene (Khirthar) fauna. Above the Sylhet Limestone there are alternations of shales, ferruginous shales, impure limestones, sandy shales, bedded sandstones, carbonaceous sandstones, and thin coal seams making up the Kopili Alternations Stage. This is of variable thickness with a maximum of about 1,500 ft. The Kopili Stage also contains foraminifera and other fossils, the fauna being only slightly different from that of the Sylhet Limestone.

The foraminifera in the Jaintia Series include *Assilina exponens*, *A. papillata*, *A. subpapillata*, *Borelis*, *Camerina acuta*, *C. atacica*, *C. obtusa*, *C. perforata*, *C. subatacica*, *Discocyclina*, *Quinqueloculina*, and *Triloculina* ; there are also numerous genera of mollusca including *Anomia*, *Chlamys*, *Ostrea*, *Teredo*, *Turritella*, and *Venericardia*.

Barail Series.—Above the Jaintia Series in the North Cachar Hills comes the Barail Series, made up largely of sandstones. These include hard, massive, moderately coarse, and usually ferruginous beds as well as bedded sandstone and shaly sandstone. In addition there are sandy shales, dark-grey shales, and many occurrences of carbonaceous and coaly shales. The Barail Series occupies a large area at the extreme eastern end of the Shillong Plateau. The beds dip gently but with some irregularity and in consequence the thickness is known only approximately; it is probably of the order of 5,000 ft. Apart from a few poorly preserved plant remains, the Barail Series in this area is unfossiliferous. There is no evidence of any break between the Kopili Alternations and the Barails.

Lower Tertiaries—South-eastern Type.

The main development of the Lower Tertiaries has been investigated in detail in the hills forming the south-eastern side of the Assam Valley and in the upper part of the Surma Valley. The succession here contrasts very markedly with the succession on the Shillong Plateau. It has been divided into two main groups:—

Barail Series.
Disang Series.

Disang Series.—The lowest division, first described by Mallet, consists of a very great thickness of unfossiliferous shales. Although no recognizable fossils have been found *in situ*, a loose block on the Disang outcrop on the north-eastern slope of the Barail Range, believed not to have travelled very far, has been found to contain Middle Eocene fossils. It is therefore fairly certain that some part of the Disang Series corresponds to the Jaintia Series. The Disang Series, however, is far thicker, possibly between 5,000 and 10,000 ft., but the whole known extent of the outcrop is sharply folded and details of thicknesses have not been worked out.

The shales are dark grey in colour, often slightly concretionary, and very finely laminated; interbedded with them are thin bands of flaggy, fine-grained, well-cemented sandstones, but except towards the top of the series these sandstones are quite subordinate. In the Naga Hills and Manipur, that is, in the hill country between the Assam Valley and the Chindwin Valley of Burma, the shales are splintery, and even slaty. Towards the centre of the hills they are traversed by veins of quartz and by an intrusive ultra-basic rock which has been altered to serpentine.

It is possible that the Disang Series in this area includes older rocks, but the inaccessible nature of the country, the dense forests, and the absence of minerals of economic value have combined to restrict geological work. The Geological Survey have recorded thin limestones and grits and a conglomerate from the hill ranges south-east of the Assam Valley, and these have been regarded as older than the main body of shales.

Barail Series.—The overlying Barail Series has been examined in very much more detail. At the north-eastern end of the Assam Valley the following divisions have been established :—

Tikak Parbat Stage.
Baragolai Stage.
Naogaon Stage.

The Naogaon Stage is composed largely of well-bedded hard grey sandstones with only minor shaly beds, and gives rise to imposing scarps in the hill country near the head of the valley. The thickness of the stage is probably between 3,000 and 5,000 ft. The sandstones making up the Naogaon Stage were originally included by Mallet in his Disang Series but it has been found convenient and more natural to include them with the Barail Series.

Overlying the Naogaon Stage comes the Baragolai Stage, made up of about 9,000 ft. of alternating clays, shales, and sandstones associated with many beds of carbonaceous shale and thin coal. The uppermost division of the Barail Series of this part of Assam is the Tikak Parbat Stage (about 1,500 ft.) which includes at its base a group of thick coal seams which are worked in the Assam coal-mines. The lowest 400 ft. is very carbonaceous and includes one seam varying in thickness from 60 feet to nearly 100 feet and another about 20 feet thick, besides a number of thinner seams. Apart from the coal seams the stage resembles the Baragolai Stage except that it is rather more arenaceous ; the separation into two stages is made possible only by the occurrence of the thick coal seams. Following the old classification, the Baragolai and Tikak Parbat Stages together are sometimes referred to as the Coal Measure Sub-series.

Plant remains are frequent in the rocks of the upper two stages and have been investigated by A. C. Seward and B. Sahni but give no precise information of age ; they have been referred to the provisional genus *Phyllites*. A few sections in the coalfield east of Margherita include a marine fossil bed ; very few identifiable specimens have been found but the fauna, which includes *Pitar agrestis* and *Tellina* (*Moerella*) *nanggulanensis*, is suggestive of an Upper Eocene age. Although this helps to place the Barail Series in the general time scale the absence of other fossil beds make it impossible to use the evidence for correlating different parts of the Barail outcrop.

When the Barail Series is traced south-westwards the amount of carbonaceous material is found to diminish rapidly and the thick seams pass into thin seams and then into carbonaceous shales. The disappearance of the criterion for distinguishing the Tikak Parbat Stage from the underlying Baragolai Stage and other lithological changes make it necessary to adopt a different classification, and for the rest of the main Barail outcrop the subdivisions are :—

Renji Sandstone Stage.
Jenam Stage.
Laisong Stage.

The approximate equivalence of the two groupings is shown in the following table :—

Renji Stage	Tikak Parbat Stage
Jenam Stage	Baragolai Stage
Laisong Stage	Naogaon Stage

The Laisong Stage, about 6,000 feet thick, is characterized by very hard, thin-bedded, well-cemented grey sandstones alternating with hard sandy shales. In addition there are moderately well bedded sandstones, massive sandstones, shales, carbonaceous shales, and thin streaks of coal. Like the Naogaon Stage it forms very prominent scarps and contributes largely to the Barail Range [1] which is the watershed between the Assam Valley and the Surma Valley.

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[1] The Barail Range is the part of the Central Assam Range near Haflong linking the Shillong Plateau with the Naga Hills.

The overlying Jenam Stage, 3,000 to 4,000 feet in thickness, with a predominance of shales, sandy shales, and carbonaceous shales, is a very much softer group. Sandstones similar to those of the Laisong Stage are present but are of much less importance and tend to be less thinly bedded.

The uppermost division of the Barail Series, the Renji Stage, includes about 3,000 feet of massive sandstone, hard, and somewhat ferruginous, with only rarely beds of shale, sandy shale, and well-bedded sandstone. This stage, too, takes part in the formation of the main hill ranges and caps the summit of the Barail Range west of Kohima where it attains a height of almost 10,000 feet.

Lower Tertiaries of Arakan.

In Ramree Island there is a small area of Cretaceous rocks and these are overlain by Lower Tertiary beds which include foraminiferal limestones of Middle Eocene age, corresponding to the Jaintia Series. Higher in the succession are beds which have yielded an Upper Eocene fauna, and it is probable that a small thickness of Barail beds occurs in Ramree and perhaps in neighbouring islands. As the Barail Series reaches a thickness of over 12,000 feet in the Surma Valley, it is surprising that more evidence of the series has not been found in the southern part of the Assam–Arakan belt; however, it may be surmised that detailed investigations in the almost inaccessible country in the hills separating the Surma Valley and Bengal from the Irrawaddy Valley would produce evidence of a considerable southerly extension of the series, especially since its counterpart in Burma extends almost as far south as the Delta.

Unconformity between the Upper and Lower Tertiaries.

The Barail Series is separated from the overlying beds by a very important break. The almost complete absence of fossil evidence makes it impossible to date the gap accurately, but from comparison with north-west India and with Burma it seems probable that the break represents a large part of the Oligocene. The identification of the unconformity above the Barail Series was a big step forward in the elucidation of Assam stratigraphy and the determination of the break in any locality makes possible a certain separation between the Lower and Upper Tertiaries. The unconformity is not marked by any sharp angular discordance, but there are rapid variations in the thickness of the Renji Stage and more rapid changes in the nature and thickness of the immediately overlying beds.

During the time interval there was sufficient uplift to permit the erosion of several thousands of feet of beds in some localities, for example, the Mikir Hills.

Upper Tertiaries.

Above the unconformity come the Upper Tertiaries divided as follows :—

Dihing Series.
Unconformity.
Tipam Series.
Surma Series.

Surma Series.—The Surma Series is comparatively thin in the north-eastern part of Assam, never exceeding 2,000 feet, and in some places being entirely absent. South-westwards there is a rapid increase in thickness to about 10,000 feet at the head of the Surma Valley and 20,000 feet in Arakan. The series has been divided as follows :—

Boka Bil Stage.
Bhuban Stage { Upper Bhuban Substage.
Middle Bhuban Substage.
Lower Bhuban Substage.

The Bhuban Stage is a monotonous sequence of sandstones, impure sandstones, shales, and impure shales. The division into three substages is made on the basis of the proportion of sandstone to shale, the Lower Substage having roughly equal amounts of shale and sandstone, the Middle Substage having much more shale than sandstone, and the Upper Substage having rather more sandstone than shale. These are, however, only rough guides, for local variation is strongly marked in both the upper and lower divisions. Besides the sandstones and shales, there are many thin and a few thick beds of conglomerate, usually of limited lateral extent ; locally the basal conglomerate includes boulders from one to two feet in diameter. The conglomerates at higher horizons are occasionally associated with evidence of local uplift and unconformity.

In Upper Assam, where the Surma Series is poorly represented, it is probable that only the Upper Bhubans are found, but the more argillaceous Middle Bhubans develop as the outcrops are followed southwards towards the Surma Valley. In the Surma Valley the Upper Bhuban Substage is from 2,000 feet to 3,000 feet thick, increasing southwards to 5,000 feet or more in Arakan. The Middle Bhuban Substage is rather thinner, but increases southwards in much the same way. The Lower Bhubans first appear in the Surma Valley where, coming as they do immediately above the unconformity, they exhibit very great changes in thickness; they thicken southwards even more markedly than do the other substages and in Arakan, although the base of the substage has not yet been found, the thickness of the Lower Bhubans probably exceeds 7,000 feet. In several localities in the Surma Valley and in Arakan thick beds of sandstone are developed in the Upper Bhubans and these give rise to very prominent scarps; the sandstone beds are lenticular and in some areas the Upper Bhubans are but little more arenaceous than the Middle Bhubans.

In the Mikir Hills the unconformity beneath the Surma Series is very well seen. The Lower and Upper Tertiary beds dip very gently, but the plane of the unconformity is irregular; the Surma Series transgresses across the Barail and Jaintia Series on to the metamorphic rocks. During the period represented by the unconformity, the Mikir Hills region was deeply eroded and the Surma Series was deposited on a surface of fairly high relief. The basal conglomerate is almost everywhere overlain by soft sandy shales and silts (Upper Bhubans and Boka Bils) which offer little resistance to weathering and erosion: in consequence the present-day denudation is rapidly removing the cover of Surma Series (with the exception of the conglomerate) and developing the fossil landscape of early Miocene times. The hard sandstones of the Barails, reinforced by the well-cemented ferruginous basal conglomerate of the Surma Series, form the higher hills, whilst much of the lower ground is still occupied by the remnants of the Surma Series. Since all the beds concerned are nearly horizontal there is a risk of the Barail sandstones on the hill tops being thought to overlie the Surma shales of the valley bottoms.

The Bhuban Stage in Assam is almost devoid of identifiable fossils. Although there are many occurrences of grits and conglomerates containing shell fragments, only one locality has so far been found containing moderately well preserved fossils that give any indication of the age of the stage. At Kanchanpur in the Surma Valley a molluscan fauna shows that the Bhuban Stage is of Lower Miocene, probably Aquitanian, age. Common genera are *Basilissa*, *Cancellaria*, *Hipponix*, *Isocardia*, and *Scutus*. In the Arakan Coast there are numerous fossiliferous localities, and although the fauna contains a very large proportion of species that are unknown elsewhere, the evidence from the known species confirms the Aquitanian age suggested by the Kanchanpur bed.

The upper division of the Surma Series, the Boka Bil Stage, is intermediate in character between the Bhuban Stage and the overlying Tipam Sandstone Stage. In its more typical development the Boka Bil Stage is associated with low, often marshy, ground in which lines of low hills mark the outcrops of the more sandy beds. A large part of the stage is made up of sandy shales or alternating laminae of shale and sand. The remaining part consists of coarse ferruginous sandstones, which are usually lenticular. The proportion of sandstone to shale shows very great variations ; in some areas the stage is made up almost entirely of sandy shale and in others the coarse ferruginous sandstones are very well developed. The Boka Bil Stage has not been identified in Upper Assam and it seems probable that it passes laterally into the lower part of the Tipam Sandstone. In the Naga Hills the stage is very thin but in the Surma Valley it reaches a thickness of 3,000 to 4,000 feet, and towards Chittagong and Arakan is about 5,000 feet thick.

The lower boundary of the Boka Bil Stage is taken at the top of that part of the sequence which includes a fair proportion of well-bedded sandstones and shaly sandstones, but from what has been said concerning the lateral variation of the Bhuban Stage and the Boka Bil Stage, it will be appreciated that in some areas the boundary is not determinable with certainty. The upper boundary shows much variation. In some sections there is such a gradual passage from the Boka Bil Stage to the Tipam Sandstone Stage that it is difficult to know where to draw a boundary line, but in other areas the line is clearly marked, and in a few sections there is evidence of a local break between the two stages. In the south-west of the Shillong Plateau the Boka Bil beds have an unusually coarse development and include several fossiliferous horizons. Amongst these are the Baghmara and Dalu fossil beds of the Garo Hills described by E. S. Pinfold and E. W. Vredenburg in 1919 and 1921. The fossils are locally numerous and even well-preserved, and indicate a Miocene age, probably Burdigalian. The following genera are well represented : *Anomia*, *Arca*, *Conus*, *Diplodonta*, *Dosinia*, *Drillia*, *Loxocardium*, *Mactra*, *Mitra*, *Nassaria*, *Natica*, *Nuculana*, *Paphia*, *Pitar*, *Rotalia*, *Sunetta*, *Terebra*, *Timoclea*, *Turris*, *Turritella*. Elsewhere in Assam the Boka Bil Stage is almost unfossiliferous. In Arakan a number of Boka Bil fossils have been found, but with the absence of fossils from the greater part of the outcrop, the palaeontological evidence is of no assistance in correlation between different parts of the region. The Arakan fossils include the following genera : *Apolymetis*, *Arca*, *Barbatia*,

Calyptraea, *Cardium*, *Chlamys*, *Conus*, *Corbula*, *Cucullaea*, *Diplodonta*, *Dosinia*, *Gastrana*, *Glans*, *Glycimeris*, *Harvella*, *Lenticulina*, *Lucina*, *Macoma*, *Mactra*, *Natica*, *Nucula*, *Nuculana*, *Oliva*, *Paphia*, *Pitar*, *Polinices*, *Rotalia*, *Siliqua*, *Sinum*, *Sunetta*, *Tellina*, *Terebra*, *Timoclea*, *Tonna*, *Trachycardium*, *Tugurium*, *Turritella*.

North of the Assam Valley it is possible that the Surma Series extends from Upper Assam westwards along the foot-hills of the Eastern Himalayas, perhaps as far as the Tista, but little evidence is available. The hills of western Bengal are fringed by Upper Tertiaries which from the scanty fossil evidence appear to include marginal representatives of the Surma Series.

Tipam Series.—The Tipam Series extends from the extreme north-west of Assam almost as far south as Akyab. It is divided into three parts :—

Num Rong Khu Stage and Dupi Tila Stage.
Girujan Clay Stage.
Tipam Sandstone Stage.

Locally in north-eastern Assam the Tipam Sandstone Stage directly overlies the Barail Series, beds with the lithology of the Surma Series being absent, and it was at one time thought that there was a passage from the Barail Series into the Tipam Series. The Tipam Sandstone Stage is distinguished by thick coarse ferruginous sandstones, but these are always associated with argillaceous beds. In the extreme north-east of Assam the argillaceous beds are mottled clays. Further south the proportion of argillaceous material is reduced and at the same time the stage increases in thickness from 3,000 feet to 6,000 feet. Still further southwards, in the Surma Valley, the mottled clays are almost entirely replaced by grey sandy shales and thin mudstones or by alternating laminae of shale and sand, and this lithological type extends to the southernmost portion of the outcrop near Akyab. Fossil wood and lignite occur sporadically in the Tipam Sandstone and in some localities the fossil wood is abundant. A few occurrences of *Batissa* in the Naga Hills do not give any evidence of age and in the rest of Assam the Tipam Sandstone is devoid of fossils. In the Arakan Coast, however, a very rich fauna has been found in the lower part of the Tipam Sandstone Stage ; the more abundant genera are : *Arca*, *Architectonica*, *Bursa*, *Calyptraea*, *Chlamys*, *Conus*, *Corbula*, *Cryptospira*, *Diplodonta*, *Ficus*, *Gari*, *Glycimeris*, *Harvella*, *Lenticulina*, *Loxocardium*, *Lucina*, *Macoma*, *Navicula*, *Nucula*, *Nuculana*, *Oliva*, *Olivancillaria*, *Ostrea*, *Paphia*, *Pinna*, *Pitar*, *Polinices*, *Quinqueloculina*, *Retusa*, *Rotalia*, *Sinum*, *Solariella*, *Spiro-*

loculina, Sunetta, Tellina, Timoclea, Tonna, Triloculina, Turritella, Vaginulina, Zozia. Unfortunately, 93 per cent of the species are not known elsewhere and consequently give no clue to the age of the stage. Of the remainder, 3 per cent are comparatively long range species, 1½ per cent are known elsewhere only from the Miocene, and 3 per cent are regarded as Pliocene forms. Palaeontological opinion is inclined to assign a Pliocene age to these fossil horizons but the apparent absence of any widespread break between the Boka Bil Stage, which is probably of Burdigalian age, and the Tipam Sandstones inclines the field geologists to place the Tipam Sandstone Stage in the Miocene.

The Girujan Clay Stage is more distinctive than any of the stages hitherto described ; it is from 3,000 feet to 5,000 feet thick and includes a large proportion of mottled clay and sandy mottled clay. In Upper Assam there is a very gradual passage from the uppermost beds of the Tipam Sandstone Stage, which are all but devoid of clay, through alternating sandstones and clays to the variegated clays which are very characteristic of the Girujan Clay Stage. Above these mottled clays come fine-grained argillaceous sandstones mottled with a purple tinge or somewhat greenish in colour. Pieces of carbonized and silicified wood are found but are not particularly common. The Girujan Clay is found in some of the Surma Valley synclines but is generally poorly exposed ; it has not been found south of Chittagong.

The highest Tipam rocks of Upper Assam, the Num Rong Khu Stage, are coarse soft sandstones of various colours, including greenish blue, bluish grey, and pale grey, weathering to orange and brown. Interbedded with these sandstones are mottled clays and beds of lignite-conglomerate. Lignite pebbles and fragments are found also in the sandstones, especially in the coarser more gritty beds. Partially silicified wood is also found in the Num Rong Khu Stage.

The corresponding beds in the Surma Valley are known as the Dupi Tila Stage. The thickness is about 6,000 feet and ferruginous, white, mottled, and coloured sands make up the greater part of the stage, but, especially near the head of the Surma Valley, there is a considerable development of mottled clay so that it becomes difficult to distinguish the Girujan Clay from the Dupi Tila beds.

Little is known about the Tertiary rocks north of the Brahmaputra Valley, but there is evidence at intervals throughout the Eastern Himalayas that beds of the Tipam Series occur in the foot-hills. The Tipam Sandstone Stage has been identified, and higher members of the series are probably present. The sandstones are characteristically pebbly and fragments of wood converted to lignite are common and have been the cause of many uninformed reports of coal. Beds which are probably of Tipam age are found at the edge of the hills in western Bengal. As might be expected in deposits of the type making up the Tipam Series, there are local unconformities : the most important is below the Dupi Tila Stage, and over a fairly large area in the Surma Valley the Girujan Stage is absent.

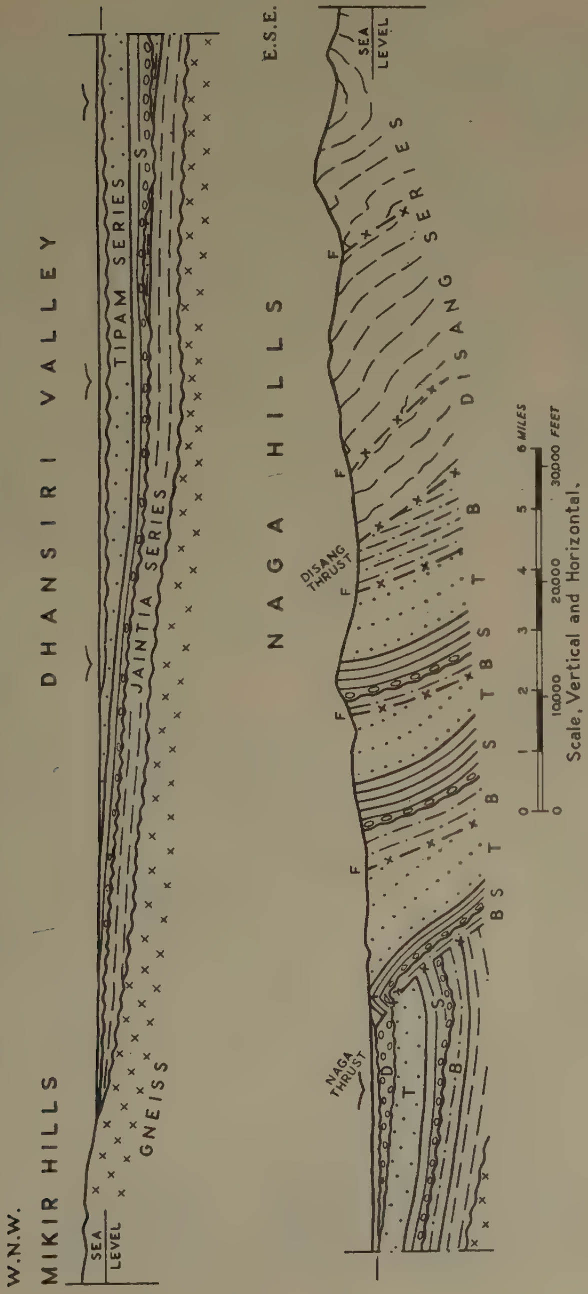
Dihing Series.—The Tipam Series is overlain by pebble-beds which reach a maximum thickness of about 5,000 feet, and were separated by Mallet as the Dihing Series. These lie unconformably either on the Num Rong Khu or Dupi Tila Stages or on the Girujan Stage. In the extreme north-east of Assam gneiss pebbles are most numerous, but elsewhere most of the pebbles are of sandstone. The matrix varies from red and mottled sand to mottled clay and soft grey clay resembling alluvial clay. Apart from badly-preserved carbonized wood and traces of leaves, the Dihing Series is entirely unfossiliferous, and there is consequently no direct evidence for its age, but it may be surmised that it corresponds to the Upper Siwaliks of north-western India. It has been involved in the major earth movements which have affected Assam and in many places Dihing pebble-beds dip at very high angles. As a result of the extensive denudation, the Dihing Series now occupies only a small part of the area which it once covered, but there are many small isolated outcrops in Upper Assam and the Surma Valley, the series has been proved beneath the Brahmaputra alluvium on the south-eastern side of the Upper Assam Valley, and occurs in the foot-hills of the Eastern Himalayas.

Pleistocene to Recent.

The deposits succeeding the Dihing Series have received very little attention. High-level alluvium occurs along the fringes of the larger valleys, reaching heights of several hundred feet or rarely nearly a thousand feet above the present river levels. The recent alluvium probably attains a very great thickness in the Brahmaputra and Surma Valleys.

IV. STRUCTURE

Almost the whole of the Tertiary belt of Assam–Arakan has been subjected to strong folding, the trend of which is for the most part roughly parallel to the general trend of the belt as shown in the map on p. 343. The folds are long, individual



TEXT-FIG. 2.—Diagrammatic cross-section through the Mikir and Naga Hills, Assam.
B = Barail Series, S = Surma Series T = Tipam Series, D = Dihing Series, F = Thrust-fault.

anticlinal axes running for many miles, and all the more sharply folded anticlines are associated with thrust faults.

In north-eastern Assam the thrusting is so strongly developed that but little remains of the anticlines, and the structure is characterized by a number of nearly parallel strike-faults running north-east–south-west. Although many of these follow nearly straight courses for many miles, there are points at which they bend very abruptly and two faults join together. The thrusts are seldom more than a few miles apart, and between them the various stages outcrop as long narrow strips ; dips are steep, and an observer unacquainted with the stratigraphy would find an apparent thickness of beds far exceeding the actual maximum thickness of the Assam Tertiaries.

This zone of overthrust faults occupies a large part of the Naga Hills. The most north-westerly fault follows closely the alluvial boundary between the hills and the alluvium of the Brahmaputra Valley, and may be termed the *Naga thrust.* It marks the division between the foreland of metamorphic rocks covered by comparatively thin gently folded sediments to the north-west and the much thicker sharply folded sediments to the south-east. Here and there along this outer fault there are structures in which the anticlinal crest remains intact at the surface, although at depth all these crests are cut out by the thrusts.

The thrust that has attracted most attention is the *Disang thrust* ; it forms the north-western limit of exposures of the Disang Series, and was at one time erroneously believed to mark the south-eastern limit of the younger Tertiaries. The Disang thrust is not the most south-easterly of the overthrusts, but the structural details of the Disang outcrop have not been worked out.

The larger faults have a throw of many thousands of feet and the horizontal movement has probably been a number of miles. The Disang thrust in places brings in contact beds which are stratigraphically 30,000 feet apart (Num Rong Khu beds against Disang Shales), and stratigraphical throws of 10,000 to 15,000 feet are common. Despite this, the beds on the underneath or downthrow side are remarkably free from disturbance : on the upthrow side there is usually only a narrow belt of disturbed rocks beyond which the beds dip steeply but regularly ; the outcrop of the Disang Series south-east of the Disang thrust is an exception, for much of the whole known extent of this series is marked by intense disturbance, and towards the centre of the hills between Assam and Burma the shales become slaty.

The belt of overthrusting narrows towards the south-west and near Haflong turns to an approximately westerly direction, becoming associated with the monoclinal fold of the southern edge of the Shillong Plateau. For some distance north-east of Haflong as well as further west, the fault belt separates the gently warped beds of the Shillong Plateau from an area in which folding rather than faulting is dominant ; this stretches from the southern part of the Naga Hills through the Surma Valley into the hills of Chittagong and Arakan. Throughout a large part of this area there are anticlines, commonly asymmetrical, separated by broader nearly symmetrical synclines. The steeper flanks of the anticlines usually show evidence of overthrusting, and in general, adjacent anticlines have their steep flanks in opposite directions.

At the extreme south of the Assam–Arakan Tertiary belt, beyond the Boronga Islands, the long narrow anticlinal folds disappear and are replaced by a much more complex structure.

West of the Ganges alluvium there is a small thickness of gently dipping Tertiary beds overlying the Gondwana and older rocks of the north-eastern part of the Peninsula.

V. Geological History

Although Gondwana rocks occur in the northern part of Assam, it seems probable that the main sedimentation of the Assam–Arakan region began with the Cenomanian transgression, which led to the submergence of some of the metamorphic rocks of the Shillong Plateau. There was, however, an interruption later in the Cretaceous and the next sediments of the western part of Assam are probably of Middle Eocene age. Further to the south-east deposition was taking place earlier in the Eocene ; the thick shales of the Disang Series, which is probably partly Lower and partly Middle Eocene, almost certainly extend right into Burma.

One of the puzzles of Assam geology is the relation between the two facies of the Middle Eocene. North-west of the Naga thrust and in Ramree Island there is the fossiliferous nummulitic limestone of the Jaintia Series ; elsewhere are the barren Disang Shales. It seems possible that the limestones were deposited along a sheltered shore-line, and that land lay not far to the north-west of the present outcrop. From another direction came the great mass of material making up the Disang Series and the equivalent beds in Burma, which include the Laungshe Shales.

Later in the Eocene there was a general shallowing of the basin and the arenaceous and carbonaceous Barail sediments were deposited; they follow the Disang Series without any apparent break, and at one time covered a very wide area. From the south-eastern margin of the Assam Valley, sandstones of the Laisong Stage of the Barail Series extend eastwards with only two small gaps to the Burma side of the hills, where they are known as the Pondaung Sandstones, and there seems to be no evidence of an effective barrier between Assam and Burma during the Eocene. The Barail Series is poorly developed in the Mikir Hills, and this is probably not entirely the result of later denudation, but indicates that the shore-line still persisted with a north-east and south-west trend. The series is absent in the western part of the Shillong Plateau and has not been identified in the Himalayan foot-hills.

In Oligocene times there was a general elevation, combined with a tilt which raised the ground in the north-west so that in Miocene times there was again a shore-line with something of the earlier trend. At first sedimentation was limited to the south of the region, but gradual submergence followed and the Miocene sea spread westwards to the borders of Bihar and Orissa, and northwards into Upper Assam. The eastern boundary of this sea is uncertain; the subsequent uplift and denudation along the Arakan Yomas, and the paucity of evidence from this little-known region, make it impossible to be sure whether during early Miocene times there was a complete separation of the Assam and Burma areas of deposition. The Miocene sediments in the southern part of the Assam–Arakan region are remarkably thick, the Aquitanian and Burdigalian Stages being represented by over 20,000 feet of beds forming the Surma Series. Westwards the Miocene thins rapidly, and probably did not extend very far beyond the outcrops now found on the fringe of the hills of Orissa, Bihar, and western Bengal.

The thick Surma Series was followed by the equally important Tipam Series, a shallower water deposit, probably laid down in fresh or brackish water in the north and in marine conditions in the south. No widespread break has been observed between the Surma and Tipam Series, but it has been suggested that Middle and possibly Upper Miocene beds are absent; and that the Tipam Series is of Pliocene age, but the intimate connection between the two series appears to be against this interpretation. During and after the Miocene transgression sedimentation was not uninterrupted; minor unconformities which may be of some local importance occur at various horizons from the Bhuban Stage to the Dupi Tila Stage, but there is no evidence of a widespread unconformity until the close of Tipam times. The local movements during the Tipam deposition were the forerunners of a more general movement which resulted in a gap between the Tipam Series and the pebble-beds of the Dihing Series. The Dihing Series may be compared to the Upper Siwaliks of Pliocene and Lower Pleistocene age found in north-western India.

There is a strip of Upper Tertiaries along the foot of the Eastern Himalayas of which comparatively little is known; the rocks have affinities with those of the Siwalik Hills and are for the most part correlated with the Tipam and Dihing Series. It is probable that there was here an important area of deposition extending westwards from Upper Assam, possibly joining the Siwalik basin of north-western India.

The movements of Miocene and early Pliocene times were the forerunners of the much greater movements that have brought about the present structure of Assam and Arakan. The distribution of the outcrops of the Tipam and Dihing Series shows that these beds must have covered a large part of Assam, and if this included parts of the Disang and Barail outcrop (as seems almost certain) an enormous thickness of material must have been removed from the areas in which Lower Tertiaries appear at the surface. The extent of the post-Miocene denudation is one of the most remarkable features of Assam geology.

VI. OIL AND GAS OCCURRENCES

In Upper Assam seepages of petroleum range from the upper part of the Barail Series to the Tipam Series, and a point of some interest is the close association of coal and oil, oil-saturated coal seams having been found. Further south the highest seepages of oil are in the Surma Series. Gas-shows are numerous, and are usually associated with salt water, and sometimes with mud. Except in Arakan, the climate is too wet for mud volcanoes to be built up as they are in the drier parts of Burma and in Baluchistan, but there are large *pungs* or mud wallows in Upper Assam. In Arakan mud volcanoes have been formed by the violent eruption of mud with sandstone ejecta derived from the country rock: during periods of quiescence the mud has been washed away, leaving mounds covered with sandstone blocks with a few tiny vents which occasionally have built mud cones up to ten feet or more in height. Numerous submarine eruptions have been recorded along the coast to the south of Akyab. The oil seepages are most numerous in Upper

Assam, towards the head of the Surma Valley, in the Boronga Islands, in Ramree Island, and in Cheduba Island. Between the head of the Surma Valley and Akyab there are very few oil-shows, but a number of gas-shows occur, especially near Chittagong.

The two oilfields (Digboi and Badarpur) and many of the oil and gas seepages are on anticlinal folds, but a number of the Upper Assam seepages are closely associated with the overthrust strike faults of the Naga Hills. The Digboi oilfield is situated on a sharply folded asymmetrical anticline with a faulted steep flank. The Badarpur oilfield was developed on a small dome, also with a faulted steep flank. The very small productions of Boronga, Ramree, and Cheduba have been obtained from shallow wells drilled near to seepages, mostly on sharply folded structures.

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Cordierite-Anthophyllite Rocks Associated with Spinel-Hypersthenites from Toodyay, Western Australia

By Rex T. Prider (Department of Geology, University of Western Australia)

I. Introduction

THE country in the vicinity of Toodyay, which is situated approximately 60 miles north-east from Perth, is occupied by a series of Archaeozoic metasedimentary and igneous rocks (Text-fig. 1). The metasediments include interbedded sillimanite- and andalusite-mica-schists, extremely pure quartzites and occasional narrow bands of calc-silicate rocks. The igneous rocks occur as (1) narrow bands of schistose plagioclase-amphibolite (interbedded with the metasediments) which appear to have been originally sills or flows of tholeiitic character; (2) wider bands of fluxion microcline- (and oligoclase-) granite-gneisses occurring as concordant thick sill-like bodies in the metasedimentary strata; (3) Quartz-dolerite dykes, intrusive into all the above-mentioned rocks. Some of these rocks, which are developed in the Jimperding valley (about 6 miles south-west from Toodyay), have been previously described (Prider, 1934).

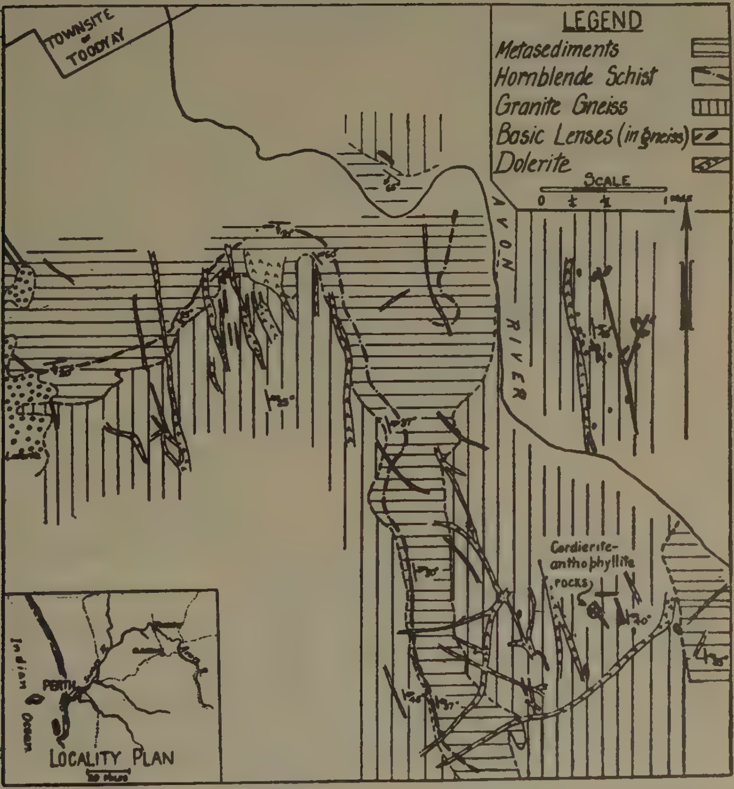
The granitic gneisses enclose xenoliths of plagioclase-amphibolite, various metasediments, and, in one place, situated 6 miles south-east of the townsite of Toodyay, a xenolith in which a variety of rock types from spinel-bearing hypersthenite to cordierite-anthophyllite rocks has been noted.

Rocks similar to the cordierite-anthophyllite rocks of this occurrence have been described from Cornwall (Tilley, 1935 and 1937) and many localities in Sweden and Finland, of which Orijärvi (Eskola, 1914) is probably the best known. Various authors have advanced rather widely different theories as to the origin of these rocks, but all agree that they are due to some form of magnesia metasomatism from different parent materials. The occurrence to be presently described appears to have originated not by any process of magnesia metasomatism, but by contamination of ultrabasic magma by aluminous material.

II. Field Occurrence

The cordierite-anthophyllite and related rocks are found occupying a small elliptical area in the centre of a band of granitic gneiss (Text-fig. 1) estimated to be approximately

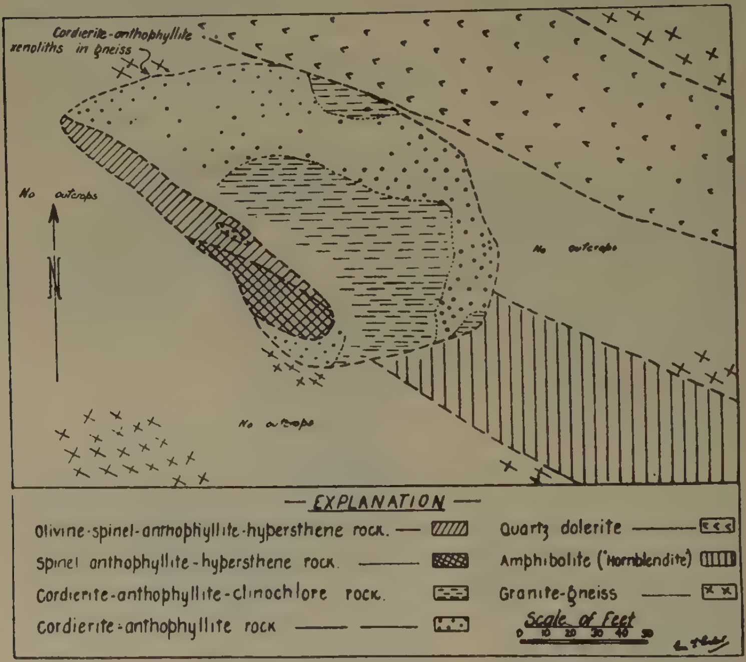
5,400 feet thick. This gneiss is characterized by the presence of numerous basic lenses which are elongated in the direction of the strike of foliation. The basic lenses are usually made up of rocks varying from coarse granular plagioclase-amphibolite to hornblendite, the only departures noted being the cordierite-anthophyllite lens and a small lenticular xenolith of a banded quartz-magnetite-hypersthene rock. Both the basic lenses and the enclosing gneiss are intersected by later quartz-dolerite dykes.



TEXT-FIG. 1.—Geological map of part of the Toodyay District, Western Australia.

The cordierite-anthophyllite xenolith (Text-fig. 2) is well exposed, but outcrops of the granitic rocks are poor, being usually covered by a thin soil mantle. Outcrops of the granitic rocks against the cordierite-anthophyllite rock are to be seen on the northern and southern edge of the mass. In the granitic gneiss on the northern edge of the mass small cordierite-anthophyllite xenoliths may be seen, indicating that the granitic material was intrusive.

The cordierite-anthophyllite xenolith is elliptical, measuring 180 feet by 100 feet, the longer axis being approximately parallel to the foliation of the enclosing gneiss. On its south-eastern edge it abuts against a narrow hornblendite lens (in the granite gneiss) which can be traced in a south-easterly direction for approximately 100 yards before it disappears. One of the later quartz-dolerite dykes mentioned in the introduction touches the north-eastern edge of the xenolith.


Cordierite-anthophyllite xenoliths in gneiss
No outcrops
N
No outcrops
No outcrops
EXPLANATION
Olivine-spinel-anthophyllite-hypersthene rock. ▨
Spinel anthophyllite-hypersthene rock ▩
Cordierite-anthophyllite-clinochlore rock.
Cordierite-anthophyllite rock
Quartz dolerite
Amphibolite ("Hornblendite")
Granite-gneiss
Scale of Feet
0 10 20 30 40 50

TEXT-FIG. 2.—Geological plan of the cordierite-anthophyllite occurrence at Toodyay, Western Australia.

Within the mass itself four distinct rock types are easily distinguishable, but as shown in Text-fig. 2 there does not appear to be any regular or zonal arrangement of these rocks. A clinochlore-anthophyllite rock occupies the greater part of the centre of the mass, and it shows a well marked system of steeply dipping joints striking parallel to the length of the lens. So far as could be seen in the field the boundaries between the different rocks are rather sharp.

III. PETROGRAPHY

The rocks of the cordierite-anthophyllite xenolith may be conveniently subdivided into five main groups within which there are various mineralogical assemblages, thus :—

A. Olivine-spinel-anthophyllite-hypersthene rocks.

(i) Olivine-pleonaste-magnetite-anthophyllite-hypersthene.

B. Spinel-anthophyllite-hypersthene rocks.

(ii) Pleonaste-magnetite-anthophyllite-hypersthene.

(iii) Biotite-pleonaste-magnetite-anthophyllite-hypersthene.

C. Biotite-clinochlore rocks.

(iv) Biotite-clinochlore-magnetite-corundum.

(v) Pleonaste-magnetite-cordierite-clinochlore-biotite.

D. Cordierite-anthophyllite-clinochlore rocks.

(vi) Pleonaste-magnetite-cordierite-anthophyllite-clinochlore.

(vii) Corundum-pleonaste-magnetite-cordierite-anthophyllite-clinochlore.

E. Cordierite-anthophyllite rocks.

(viii) Cordierite-anthophyllite (with rare quartz).

(ix) Biotite-cordierite-anthophyllite (with rare quartz and plagioclase).

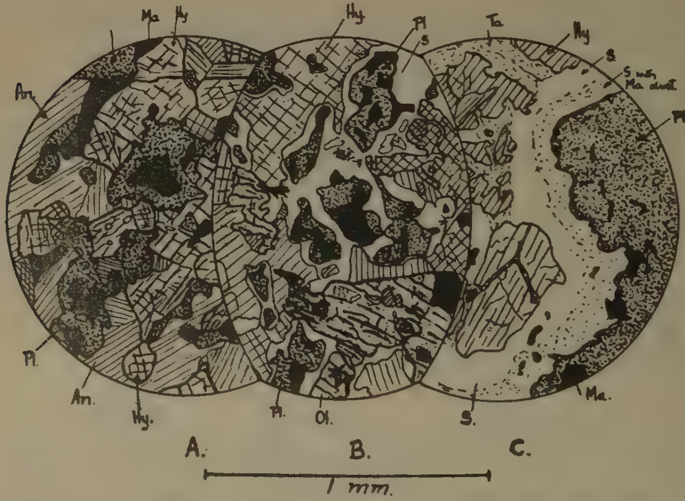
(x) Biotite-hypersthene-cordierite-anthophyllite (with rare quartz and plagioclase).

(i) *Olivine-pleonaste-magnetite-anthophyllite-hypersthene rocks*

These are dark coloured, heavy (S.G. 3.33) rocks with a fine even-grained appearance. Closer examination of fracture surfaces in favourable lighting shows glistening plates of pyroxene up to 1 cm. diameter, the continuity of which is interrupted by dull lustred inclusions. Under the microscope the rock is seen to consist largely of plates of hypersthene (with inclusions of spinel, magnetite, and anthophyllite) together with plates of olivine (with spinel-magnetite inclusions)—apatite and phlogopite are minor accessories. The hypersthene forms the bulk of the rock—it is in irregularly cracked plates showing considerable alteration to fine fibrous highly birefringent talc along cracks and cleavages. It is a weakly pleochroic variety, is optically negative and has $\beta = 1{\cdot}724$ indicating the presence of approximately 55 mol. % $FeSiO_3$. The amphibole is in well shaped prisms, always idioblastic towards the hypersthene, often penetrating or being completely enclosed in the latter. It is practically colourless, but in thicker section shows pleochroism : $\alpha = \beta$ colourless, γ pale clove brown. Its other optical properties : $\gamma \parallel c$, $\gamma = 1{\cdot}660$ $\beta = 1{,}652$ (+) 2V large indicate an anthophyllite with approximately 35 per cent of the $FeSiO_3$ molecule.

Olivine is in irregularly cracked plates to 3 mm. or more diameter, enclosing spinel, and with considerable fine granular magnetite along irregular cracks. It is colourless, optically negative with 2V near 90°, and has $\beta = 1{\cdot}694$, $\alpha = 1{\cdot}680$ indicating a chrysolite ($Fa_{22}Fo_{78}$).

The spinel is a dark green variety in irregular shaped granules averaging 0·4 mm. diameter and is very abundant, forming approximately 20 per cent of the rock. It has a refractive index 1·780 and is therefore an iron-rich pleonaste. It is closely associated with magnetite. At its contact with hypersthene and olivine there is usually developed a narrow rim of colourless, feebly birefringent serpentine (Text-fig. 3, B and C). These reaction rims are considerably wider in the next group to be



TEXT-FIG. 3.

A. Pleonaste-magnetite-anthophyllite-hypersthene rock. In this rock there are no reaction rims on the pleonaste (Pl).
B. Spinel-olivine-anthophyllite-hypersthene rock showing serpentinous rims (S) around pleonaste (Pl). Also shows pleonaste enclosed by olivine (Ol) and hypersthene (Hy).
C. Coarser grained spinel-anthophyllite-hypersthene rock showing a more advanced stage of reaction between the pleonaste and hypersthene. Parts of the reaction rim nearest the pleonaste are dusted with magnetite. Small islands of magnetite remain in the serpentinous material (S). The hypersthene shows alteration in places to talcose material (Ta).

described and the properties of this material are more fully described there. Several specimens which fall in this group do not have this structure developed (Text-fig. 3A). A chemical analysis of this rock is given in Table 2.

(ii) *Pleonaste-magnetite-anthophyllite-hypersthene rocks*

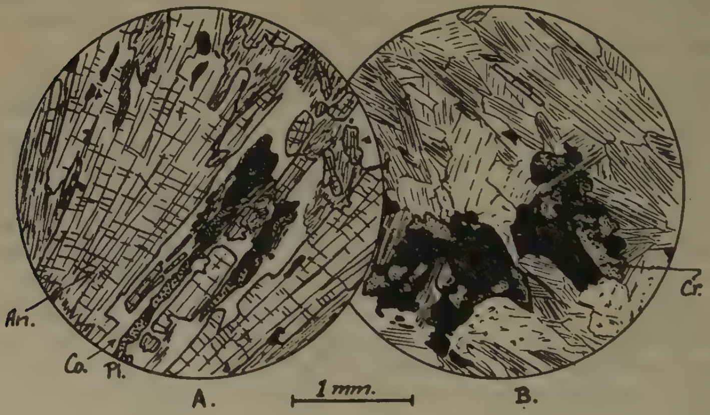
Rocks of this group are very similar mineralogically to (i) but differ in being much coarser textured, having no olivine (although rare talc-magnetite areas show that it was originally present) and having much wider rims on the pleonaste. Phlogopite is a rare accessory, occupying the interstices between the anthophyllite prisms.

The pleonaste in these rocks is in plates up to 3 mm. diameter, which are surrounded with serpentinous rims up to 0·5 mm. wide (Text-fig. 3, C). This serpentinous material is pale yellow and shows low " flecked " polarization colours. It has $\beta = 1{\cdot}600$, $\gamma - \alpha$ approximately ·005 and γ is normal to (001), the mineral appearing to be a prochlorite ($\mathrm{Ant_2Fe.Ant_1\ Dn_2\ At_5}$). This mineral is clearly a reaction product of the (Fe, Mg) silicates with the aluminous spinel. The edges of the spinel during this process become very ragged and it breaks up into small grains. All changes from the rocks described under (i) where the rims are absent or very thin to highly altered types where most of the spinel and hypersthene (together with olivine and anthophyllite) have been replaced by this serpentinous material have been noted. Three stages are shown in Text-fig. 3. The magnetite inclusions in the pleonaste remain as islands in this alteration product. In certain clinochlore-rich rocks to be described presently, cordierite porphyroblasts enclosing anthophyllite prisms, irregular shaped grains of magnetite and rare pleonaste remnants have been noted (Text-fig. 5A) — such porphyroblasts appear to represent a recrystallization of the serpentinous reaction product between the pleonaste and (Fe, Mg) silicates to cordierite.

(iii) *Biotite-pleonaste-magnetite-anthophyllite-hypersthene rocks*

These occur closely associated with (ii) and have the same structure. They are very coarse grained rocks containing anthophyllite prisms up to 1 inch long and differ from group (ii) only in the presence of the pale brown mica which is present in decussate-structured aggregates of flakes averaging 1 mm. diameter and forming approximately 30 per cent of the rock. This mica is a strongly pleochroic phlogopite with $\beta = \gamma$ reddish brown, α colourless to pale brown, (—) 2V very small, practically uniaxial, $\alpha = 1{\cdot}574 \pm {\cdot}002$, $\gamma = 1{\cdot}615 \pm {\cdot}002$.

The magnetite-pleonaste association which is so common in types (i) and (ii) is present and serpentinous rims are developed where the pleonaste is in contact with the phlogopite—these rims are dusted with magnetite. Hypersthene is in irregularly cracked plates to 3 mm. diameter and carries inclusions of phlogopite and spinel, the latter being rimmed with serpentine. Anthophyllite is in idioblastic prisms enclosing spinel. The spinel, hypersthene and anthophyllite are similar in all respects to the minerals described in the two preceding groups.



TEXT-FIG. 4.

A. Corundum - spinel - cordierite - anthophyllite - clinochlore rock, showing radiating anthophyllite prisms (An) and fibrous clinochlore. The anthophyllite encloses pleonaste-magnetite aggregates (Pl) which are rimmed with cordierite (Co).

B. Corundum - magnetite - clinochlore - biotite rock — showing magnetite corundum (Cr) intergrowths in a slightly schistose clinochlore-biotite ground with rare relict prisms of anthophyllite.

The average mineralogical composition of rocks of this group is estimated to be : hypersthene 40 per cent by volume, anthophyllite 10 per cent, phlogopite 30 per cent, pleonaste + magnetite 20 per cent.

(iv) *Magnetite-corundum-biotite-clinochlore rocks*

This assemblage was noted only in a narrow band, 3 inches wide, in the normal cordierite-anthophyllite rock. It is a greenish schistose rock made up almost entirely of flakes, 1 to

2 mm. long, of greenish brown mica with some clinochlore and irregular lenticular magnetite-corundum aggregates. The mica is greenish brown with α colourless to very pale yellow green, $\beta = \gamma$ brownish green, (—) 2V very small, almost uniaxial, $\beta = 1{\cdot}615 \pm {\cdot}002$. The clinochlore, which is similar to that in the cordierite-bearing rocks, appears to be developed from the biotite. The magnetite and corundum are always closely associated—the lenticular aggregates (Text-fig. 4B) appear to be single crystals of corundum with magnetite intergrowths, as all of the corundum grains extinguish simultaneously. The association is similar to that of pleonaste and magnetite in the rocks of group (i) and all three of these minerals are associated in rocks of group (vii). The corundum is the bluish pleochroic variety (sapphire) with pleochroism ϵ colourless, ω deep Prussian blue.

The approximate mineralogical composition of this rock is: biotite 75 per cent by volume, clinochlore 10 per cent, magnetite 10 per cent, corundum, 5 per cent. The results of a chemical analysis of this rock are shown in Table 2.

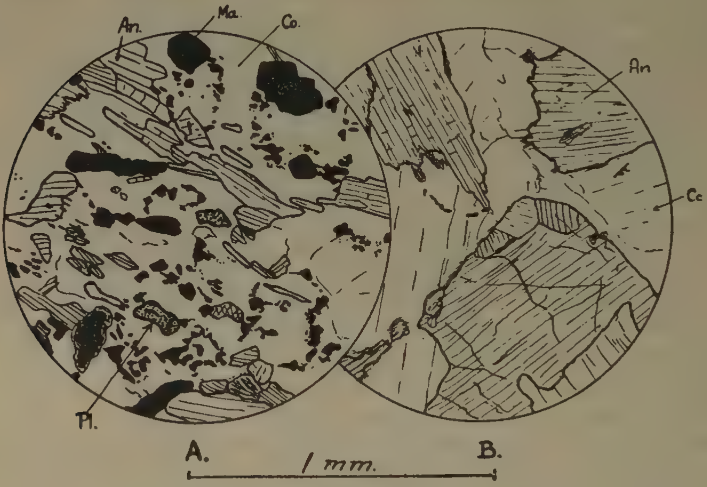
(v) *Pleonaste-magnetite-cordierite-clinochlore-biotite rocks*

One specimen only of this type was collected—it came from near the eastern edge of the mass where it is entirely enclosed by the normal cordierite-anthophyllite rock. It is a slightly schistose, dark greenish rock which, under the microscope, is seen to consist of a decussate-structured aggregate of greenish brown biotite (20 per cent) and pale greenish clinochlore (40 per cent) with patches of almost completely pinitised cordierite (35 per cent). The biotite is identical with that in group (iv) and the clinochlore (which is idioblastic towards the biotite) has the properties: $\alpha = \beta$ pale greenish, γ colourless, $\beta = 1{\cdot}592 \pm {\cdot}002$, (+) 2V small, almost uniaxial. Magnetite is present as recrystallized octahedra and frayed skeletal grains enclosed in cordierite—there are no remnants of the pleonaste present in this rock. Accessory apatite is present in rare stout prisms.

(vi) *Pleonaste-magnetite-cordierite-anthophyllite-clinochlore rocks*

These form a large part of the xenolith (Text-fig. 2). They are massive, greenish chloritic rocks with irregularly oriented anthophyllite prisms (but in several specimens the anthophyllite prisms up to 5 mm. long are radially arranged). Throughout these rocks occasional dull dark greyish cordierite knots up to $\frac{3}{4}$ inch diameter are visible. The groundmass of the rock is a decussate aggregate of clinochlore (similar to that in (v)) with prisms of anthophyllite which appear to be relicts of earlier larger prisms. The clinochlore carries numerous magnetite inclusions in the form of recrystallized octahedra. This groundmass of the rocks is made up approximately of clinochlore (75 per cent by volume), anthophyllite (20 per cent) and magnetite (5 per cent).

The large cordierite porphyroblasts are crowded with inclusions of prismatic anthophyllite, clinochlore flakes, magnetite in recrystallized octahedra and skeletal remnants, and rare pleonaste remnants. In most cases the pleonaste has almost disappeared and left the irregular shaped magnetite grains (Text-fig. 5A) but the occasional remnants form a clear link between rocks of this group and groups (i), (ii) and (iii).



TEXT-FIG. 5.

A. Section of a cordierite porphyroblast from cordierite-anthophyllite-clinochlore rock. The clear part of this field is occupied by a single crystal of cordierite (Co) which encloses magnetite (black), anthophyllite (An) and rare remnants of pleonaste (Pl).

B. Cordierite-anthophyllite rock showing the typical granoblastic structure of this group. Minerals present are anthophyllite (An) and cordierite (Co) with minor amounts of magnetite and fibrous chlorite fringing the anthophyllite.

(vii) *Corundum-pleonaste-magnetite-cordierite-anthophyllite-clinochlore rocks*

These are essentially the same as the rocks of group (vi) with the addition of corundum which is associated with pleonaste and magnetite. The corundum is the same bluish pleochroic variety as described above—that this is sapphire and not sapphirine is seen in its uniaxial character. In some rocks of this group the anthophyllite prisms are in radial arrangement interrupted by cordierite areas containing central pleonaste-magnetite inclusions (Text-fig. 4A)—the cordierite here clearly represents a recrystallization of the serpentinous product of the reaction between the pleonaste and anthophyllite as described above. An analysis of a member of this group is given in Table 2.

(viii) *Cordierite-anthophyllite rocks*

Rocks of this group are coarsely granular, consisting of greyish cordierite and anthophyllite (in prisms up to 1·5 cms. long). The microstructure is coarse granoblastic (Text-fig. 5B), the cordierite occurring in xenoblastic plates to 2 mm. diameter and the anthophyllite in clots of prismatic crystals usually rimmed with a yellowish-green serpentine and rarely with flaky clinochlore. Accessories are magnetite, zircon and quartz.

The cordierite plates are extensively cracked and pinitised. Zircon inclusions are surrounded by intensely pleochroic haloes which have an inner weakly pleochroic zone and an outer strongly pleochroic halo. The cordierite of all these rocks appears to be uniform in character with (—) 2V large and $\alpha = 1{\cdot}542 \pm {\cdot}002$, $\gamma = 1{\cdot}550 \pm {\cdot}002$. The anthophyllite is a pale clove coloured variety with α light clove brown, β light clove brown, γ deeper clove brown, absorption $\alpha<\beta<\gamma$, (±) 2V near 90°, $\gamma = 1{\cdot}647 \pm {\cdot}002$, $\gamma = 1{\cdot}663 \pm {\cdot}002$, $\gamma - \alpha = {\cdot}016$, indicating an anthophyllite with approximately 40 per cent by weight of $FeSiO_3$. The negative optical character of some of this amphibole indicates that it is the aluminous variety gedrite.

Oligoclase and quartz are rare accessories in this type. The oligoclase encloses irregular shaped grains of cordierite and appears to be secondarily introduced. It shows fine lamellar twinning with straight extinction in the symmetrical zone indicating oligoclase (Ab_4An_1).

(ix) *Biotite-cordierite-anthophyllite rocks*

These are coarse grained rocks in which plates of pale brownish biotite (to 5 mm. diameter) and prisms of anthophyllite (to 1·5 cm. × 0·7 cm.) can be recognized in a finer grained, greasy lustred granular ground of cordierite. In several of these specimens small quartz veinlets are present—this material is evidently derived from the intrusive granite (gneiss) which completely surrounds the cordierite-anthophyllite xenolith. Under the microscope the constituents recognized were: cordierite, anthophyllite, phlogopite and accessory zircon, magnetite and apatite. The anthophyllite and cordierite have the same characters as described in the previous group, the former occurring in idioblastic prisms, often showing alteration to a pale greenish chlorite and the latter in xenoblastic equidimensional plates to 3 mm. diameter with alteration to fine fibrous pinite along irregular fractures.

TABLE I

	I	II	III	IV	V
SiO_2 . .	49·73	52·66	47·07	48·00	46·96
Al_2O_3 . .	12·70	13·99	20·20	18·62	14·13
Fe_2O_3 . .	4·56	2·15	0·00	1·07	0·76
FeO . .	12·27	7·08	12·73	16·18	14·95
MgO . .	16·59	20·20	10·09	11·85	15·97
CaO. . .	Tr.	0·25	2·14	0·64	2·32
Na_2O . .	0·40	0·08	1·48	0·23	0·35
K_2O . .	0·54	0·06	1·97	0·01	1·68
H_2O + . .	2·77	3·33	1·50	1·50	1·26
H_2O − . .	0·12	0·13	0·16		0·07
TiO_2 . .	0·21	0·36	2·12	2·06	0·62
P_2O_5 . .	Tr.	0·05	0·12	0·09	0·03
MnO . .	Nil	0·12	0·11	0·13	0·93
Cr_2O_3 . .	Nil	0·19	0·02	0·04	Tr.
Others . .	—	0·02	0·50	0·15	0·06
	99·89	100·67	100·21	100·57	100·09

I. Biotite-cordierite-anthophyllite rock, Toodyay, Western Australia. Anal. R. T. Prider.

II. Cordierite-anthophyllite rock, Clackline, Western Australia. (*Journ. Roy. Soc. West. Aust.*, vol. xxiv, 1937–8, p. 115.)

III. Anthophyllite-cordierite-hornfels, Carn Kenidjack, Cornwall. (*Geol. Surv. Great Britain Summ. Prog. for 1929*, pt. 2, p. 28.)

IV. Anthophyllite-cordierite-hornfels, Träskböle, Orijärvi, Finland. (*Bull. Comm. Géol. Finlande*, No. 40, 1914, p. 171.)

V. Granulitic hypersthene-gabbro, Gunflint Lake, Cook Co., Minnesota, U.S.A. (*Journ. Geol.*, vol. iii, 1895, p. 10.)

The mica is in well shaped flakes idioblastic towards the cordierite. It is a strongly pleochroic reddish brown variety with $\beta = 1\cdot609$ and very small 2V. The most usual occurrence is in small aggregates, often including magnetite and zircon, the latter being surrounded by pleochroic haloes. This mica is similar (although it has slightly lower refractive indices) to that in the anthophyllite-hypersthene rocks (group iii above).

As in the preceding group, quartz and oligoclase may be present in accessory amounts. An analysis of this rock is given in Table 1.

(x) *Biotite-hypersthene-cordierite-anthophyllite rocks*

This association is represented by a single specimen from a small lenticular area completely surrounded by the spinel-anthophyllite-hypersthene rock (Text-fig. 2, about 20 feet south-west from the centre of the mass). The specimen exhibits a rude banded structure—dark coloured bands consisting mainly of anthophyllite and hypersthene with occasional flakes of phlogopite alternating with light coloured bands consisting of a granoblastic aggregate of cordierite and quartz with rare prisms of anthophyllite. The anthophyllite is clearly developed from the hypersthene and inclusions of magnetite seem to indicate that the anthophyllite is poorer in iron than the original hypersthene. The cordierite is in the usual equidimensional xenoblastic forms while the quartz is in elongated grains with their longer axes parallel to the banding of the rock. It is difficult to say here whether the quartz has been secondarily introduced or whether it is an original constituent of the rock—the fact that anthophyllite sometimes partly encloses quartz possibly indicates that the quartz is an older constituent and has not been secondarily introduced like the quartz in the rocks of groups viii and ix.

The Associated Rocks

(*a*) *The Granite-gneiss.*—This forms the country which completely encloses the cordierite-bearing rocks and its intrusive character can be seen by the presence, on the northern edge of the cordierite mass, of xenoliths of cordierite-anthophyllite rock within the gneiss. Normally this rock is made up of oligoclase (30 per cent by volume), slightly microperthitic microcline (30 per cent), quartz (30 per cent) and greenish partly chloritised biotite (10 per cent) with accessory apatite, magnetite and very rare sphene and epidote. In the specimens from the northern edge of the cordierite-anthophyllite mass the gneiss is considerably modified by the inclusion of clots of (1) reddish brown phlogopite, (2) phlogopite with anthophyllite, (3) cordierite-anthophyllite-phlogopite rock and xenocrysts of cordierite and anthophyllite, the latter often rimmed with pale coloured phlogopite.

(*b*) *The Amphibolite.*—The amphibolites are also xenolithic in the granite-gneiss and have been noted right through the

Toodyay area. They occur in lenticular masses and are somewhat variable in character from granular monomineralic hornblende rocks to granular plagioclase-amphibolites. The amphibolite band in the vicinity of the cordierite-anthophyllite rocks is the monomineralic variety, consisting entirely of a deep bluish green hornblende with α = yellow green, β = dark olive green, γ = deep bluish green, $\alpha < \beta \gg \gamma$, $\beta = 1{\cdot}675$.

The contact of this "hornblendite" with the cordierite-bearing rocks is sharp, and field relations suggest that there is no genetic relation between the two groups of rocks. Other basic lenses are traversed by narrow irregular acid veinlets from the gneiss—a clear indication of the pre-gneiss age of the basic lenses.

(*c*) *The Quartz-dolerite.*—This rock is the latest intrusive in the Toodyay area. It is a normal quartz-dolerite and requires no further description. It comes into contact with the cordierite-bearing rocks but a close search indicates that it has produced no effect on the older rocks and is constant in character (except grain size) throughout the dyke, so that it has not assimilated any of the cordierite rocks.

IV. CHEMICAL ANALYSES

Analyses have been made of four of the more important types and these serve to show the close relationship of the spinel-hypersthene and cordierite-anthophyllite rocks. All these analyses (which appear in Table 2) are abnormal, either for igneous or sedimentary rocks. The main features are the abnormally high percentages of magnesia, iron oxides and alumina, the absence of lime and the very low figure for alkalies (except in the biotite-rich type of analysis II). Tilley and Flett (1930, p. 34) have drawn attention to the abnormality of composition of the cordierite-anthophyllite rocks of Cornwall and Orijärvi—the abnormalities of the Toodyay rocks described in this paper are even more marked than those of Cornwall.

The close relationship between the spinel-hypersthene rocks and the cordierite-anthophyllite rocks suggested by the field occurrence (Text-fig. 2) is borne out by their chemical features, viz. the abnormally high alumina, magnesia and iron oxides together with the absence of lime in all rocks analysed. There is only one feature which is disturbing to this relationship and that is the presence in the hypersthene-rich type of appreciable Cr_2O_3 and its absence from all the other rocks. The cordierite-anthophyllite rock has a higher SiO_2 content than the other types, but after subtracting 27 per cent of SiO_2 and recalculating to 100 it becomes almost identical with the others (Table 2, Col. V).

In Table 1 the Toodyay cordierite-anthophyllite rock is compared with similar rocks from other localities. It is very similar to the rock from Clackline, Western Australia (Simpson, 1938, p. 115) and differs from the Kenidjack and Orijärvi rocks only in its somewhat lower alumina, absence of lime and higher magnesia and iron oxides.

TABLE 2

ANALYSES OF SPINEL BEARING HYPERSTHENITE AND RELATED ROCKS FROM TOODYAY, WESTERN AUSTRALIA

	I	II	III	IV	V
SiO_2	30·91	30·83	33·20	49·73	30·8
Al_2O_3	21·36	20·47	19·75	12·70	17·5
Fe_2O_3	19·97*	9·23	3·36	4·56	6·3
FeO	—	11·28	13·23	12·27	16·9
MgO	23·57	16·10	21·57	16·59	22·9
CaO	Tr.	Tr.	Nil	Tr.	—
Na_2O	Nil	0·36	0·24	0·40	0·6
K_2O	Nil	5·18	0·22	0·54	0·7
H_2O+	2·58	4·87	8·43	2·77	3·9
H_2O-	0·90	0·42	0·10	0·12	0·1
TiO_2	1·66	0·70	0·06	0·21	0·3
P_2O_5	Tr.	nd.	nd.	Tr.	—
MnO	0·16	0·07	0·14	Nil	—
Cr_2O_3	0·17	Nil	Nil	Nil	—
	101·28*	99·51	100·30	99·89	100·0

I. Olivine-spinel-anthophyllite-hypersthene rock (i), Toodyay, Western Australia. Anal. R. T. Prider.

II. Biotite-clinochlore-magnetite-corundum rock (iv), Toodyay, Western Australia. Anal. R. T. Prider.

III. Corundum-spinel-anthophyllite-cordierite-clinochlore rock (vii), Toodyay, Western Australia. Anal. R. T. Prider.

IV. Biotite-cordierite-anthophyllite rock (ix), Toodyay, Western Australia (quoted in Table 1).

V. Analysis IV from which 27·3 per cent of SiO_2 has been subtracted and then recalculated to 100 (for comparison with I).

* Owing to very high pleonaste content FeO was not determined and total iron is quoted as Fe_2O_3, thus giving high summation.

With regard to the spinel-olivine-hypersthene rocks there does not appear to be any record of mineralogically similar rocks from any other locality, but certain mineralogical associations from the Kenidjack occurrence (Tilley and Flett, 1930) are comparable with the corundum-spinel-clinochlore-cordierite-anthophyllite rocks of Toodyay.

V. PETROGENESIS

Various theories regarding the origin of the cordierite-anthophyllite assemblage have been advanced during the last twenty-five years. Eskola (1914) has shown that the cordierite-anthophyllite rocks of Fennoscandia are siliceous leptites of volcanic origin which have been metasomatised by iron-magnesia solutions from the intrusive granite-gneisses in which they are enclosed (note the similarity in occurrence to the Toodyay rocks). Tilley considers that similar rocks at Kenidjack (Tilley, 1935) and the Lizard (Tilley, 1937) are developed from basic igneous rocks by an internal magnesia metasomatism (involving the removal of lime during weathering followed by contact alteration and addition of silica and potash) and that the assemblage anthophyllite-staurolite-cordierite from the Lizard has been developed by the regional metamorphism of argillaceous sediments (Tilley, 1937, p. 307). Osborne (1939, p. 719) considers that the anthophyllite-cordierite rocks of Montauban, Quebec, are magnesia-metasomatised gneisses and Simpson (1938, p. 116) suggests that similar rocks from Clackline, Western Australia (see locality plan (Text-fig. 1)), were developed from a hypersthenite, which during its emplacement absorbed some slate or similar aluminous material. A recent examination of this occurrence has been made by the author, who has found that the cordierite-anthophyllite mass is of uniform composition throughout and that there is no hypersthene-bearing rock associated with it as there is at Toodyay. Nevertheless the author, while working on the Toodyay cordierite-anthophyllite rocks at Cambridge in 1937–8, came independently to the same conclusions as advanced by Simpson (Prider, 1938, p. 76).

In the Toodyay xenolith, the olivine-spinel-anthophyllite-hypersthene rock can reasonably be regarded as a direct crystallization product of a magma, for it shows considerable relict olivine ; the sequence of minerals (spinel, olivine and finally hypersthene) follows the normal reaction series ; and the microstructures (with the exception of the later crystalloblastic growth of anthophyllite) are typical of a medium grained pyroxenite. In its abundance of magnesia and iron oxides and absence of lime and alkalies it was an ultrabasic type, consisting originally of spinel, olivine and very abundant hypersthene (a spinel-olivine-hypersthenite). The fact that the spinel is enclosed in the olivine indicates that this mineral was an original constituent of the rock of earlier crystallization than the olivine and hypersthene. In view of this original abundance of spinel (pleonaste) the *original magma* must have been abnormally rich in alumina. How this abnormal alumina content was developed is not clear but the presence of sillimanite-schists (with 50 to 60 per cent of sillimanite) in the pre-gneiss metasedimentary series of this district (see Introduction) points to the possibility that the alumina was derived from similar sediments which were invaded by the hypersthenite magma, the contamination process being similar to that described by Read (1935) in connection with the cordierite-norites of the Haddo House district and by Bowen (1928, Chap. X) when dealing with the effects of basic magma on aluminous sediments.

The mode of formation of the spinel-olivine-anthophyllite-hypersthene rocks seems to have been : firstly, a contamination of an ultrabasic magma by the assimilation of aluminous sediments, followed by the early separation of iron-rich spinel and later by the separation of olivine and hypersthene. During a later period the action of shearing stresses under lower temperatures has given rise to the anthophyllite which has developed at the expense of the hypersthene (see Phillips, 1930). These minerals have suffered a post-crystallization alteration to talcose material and there has been some reaction between the earlier formed spinel and the later (Fe, Mg) silicates giving rise to serpentinous material. There does not appear to have been any addition of material to this rock from the intrusive granite (gneiss) in which the xenolith occurs, except possibly in the phlogopite-bearing rocks of association (iii) (although from the microstructure the phlogopite appears to have been of early crystallization).

The reaction rims around the spinel are an important link between the hypersthenites and the cordierite-anthophyllite rocks—all stages in the development of these rims are to be seen. In rocks of group (i) the rims are very narrow or absent, in the coarser rocks of group (ii) they are much wider (Text-fig. 3) and finally the cordierite and clinochlore rocks appear to represent a stage where reaction between the spinel and ferromagnesian silicates has been complete and the reaction product has been recrystallized. In the hypersthenites these rims are made up of an aluminous prochlorite developed thus :—

(*a*) Pleonaste + hypersthene + water → prochlorite + silica.
(*b*) Pleonaste + hypersthene + olivine + water → prochlorite.

The clinochlorite-anthophyllite rocks could be developed by a similar reaction to (*a*), the extra silica going into the more siliceous clinochlore thus :—

(*c*) Pleonaste + hypersthene + water → clinochlore.

The almost identical character of analyses I and III (Table 2) indicates that this reaction has taken place; the original rock from which III was derived contained more silica and less alumina (i.e. no olivine and less spinel) than the spinel-olivine-hypersthenite.

Microscopical evidence shows that this chloritization took place prior to the development of the cordierite. The development of cordierite porphyroblasts in the clinochlore rocks has been described (under associations vi and vii)—the occasional relicts of pleonaste represent the pleonaste of the original pleonaste-hypersthene rock from which all of the hypersthene has disappeared by reaction with the pleonaste. With a larger replacement of the clinochlore by cordierite we get a transition to the cordierite-anthophyllite rocks. The change of clinochlore into cordierite requires the addition of silica with some alumina and this is reflected in the analyses (i.e. in Table 2, analysis IV is considerably richer in SiO_2 than the spinel-bearing types. See also the analyses of the Kenidjack rocks (Tilley, 1930, pp. 28 and 33)). The presence of corundum in many of the clinochlore rocks indicates that corundum was the source of the alumina and that it was an original constituent of similar origin to the pleonaste. The addition of silica may have been effected by :—(1) The assimilation of more siliceous material in certain parts of the original hypersthenite intrusion than in others, or (2) The addition of silica from the intrusive granite.

A glance at Text-fig. 2 will show that wherever the gneiss is seen in contact with the xenolith, the xenolithic rock is the more siliceous cordierite-anthophyllite type. On the western edge no gneiss can be seen in contact with the hypersthene-rich rock, which may be surrounded here by the cordierite-anthophyllite rock (obscured by soil mantle). This may indicate that the extra silica required to produce the cordierite rock from the spinel-hypersthene rock was derived from the granite, and this is supported by the occurrence in the cordierite-anthophyllite rocks of rare quartz veinlets and secondary oligoclase.

A similar occurrence of the association of cordierite with clinochlore has been described by Tilley (1930, p. 33) from Kenidjack. In this occurrence Tilley considers that the clinochlore has been pneumatolytically developed from the cordierite, but in the Toodyay rocks the cordierite porphyroblasts enclose remnants of clinochlore and are clearly developing from the clinochlore. The development of the cordierite porphyroblasts is a contact effect and must have taken place during the intrusion of the granite as the only other intrusive (the quartz-dolerite dyke) does not appear to have affected any of the older rocks.

VI. CONCLUSION

There can be no doubt, after a consideration of the field relations, mineralogical assemblages and chemical data, that the cordierite-anthophyllite assemblage is genetically related to the spinel-olivine-hypersthene rock and was derived from it by the simple addition of silica (probably from the granite) and contact metamorphism (consequent upon the intrusion of the granite). The spinel-olivine-hypersthene rock is considered to have originated by crystallization from a hypersthenite magma which has been contaminated by assimilation of aluminous material. The clinochlore rocks have developed by the reaction of pleonaste with the hypersthene and olivine under hydrothermal conditions (such as obtain during the serpentinization of ultrabasic masses during their final stages of consolidation) and the cordierite-anthophyllite assemblages have been developed during the period of intrusion of the granite-gneiss by addition of silica from the granite.

The above theory of the genesis of these cordierite-anthophyllite rocks differs considerably from the theories advanced by Eskola (1914), Tilley (1935 and 1937) and Osborne (1939) for the origin of similar rocks, and further emphasizes the statement that " the anthophyllite-cordierite assemblage provides a remarkable example of mineral convergence in metamorphism " (Tilley, 1937, p. 308).

VII. ACKNOWLEDGMENTS

Part of the work on these rocks was carried out at the Department of Mineralogy and Petrology, Cambridge, during the tenure of a Hackett Research Studentship from the University of Western Australia. The author desires to thank Professor C. E. Tilley for his advice and criticism in connection with these rocks and Professor E. de C. Clarke for assistance in the field and during the revision of the text.

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The Composition and Properties of Shore and Dune Sands

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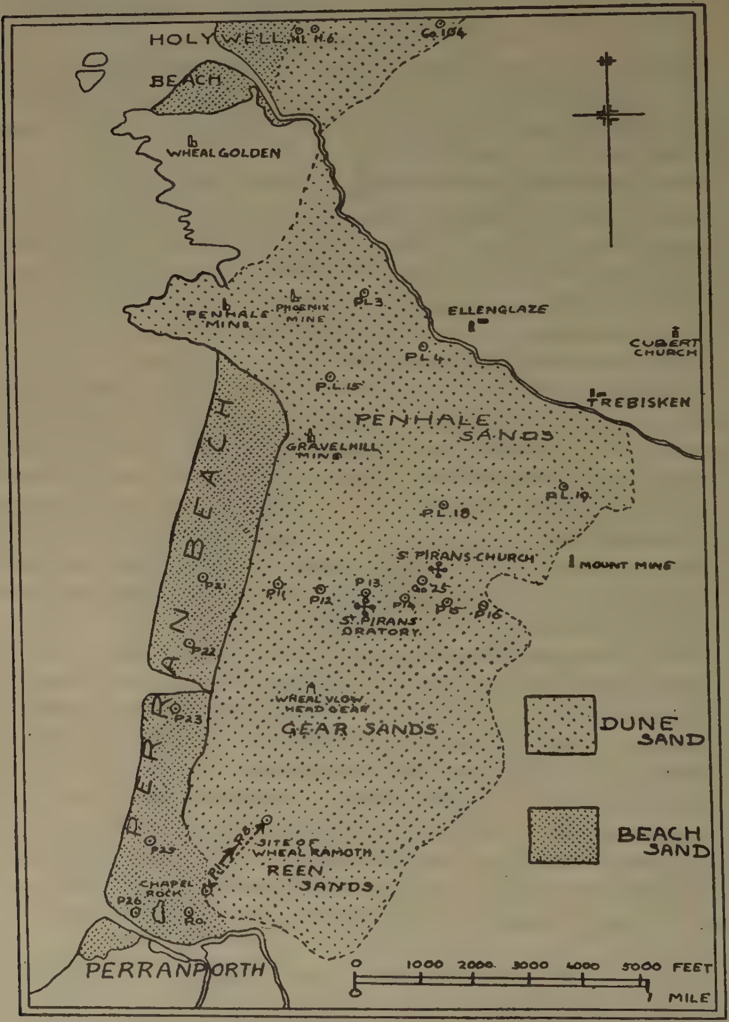
THIS work was undertaken in an attempt to assess the significance of minor variations in composition and properties of sand samples collected from the same locality and derived from a common source.

Most of the samples examined came from the neighbourhood of Perranporth on the north coast of Cornwall. This particular locality was chosen as offering the largest extent of shore and dune sands available for study. Perran beach affords a stretch of shore over two miles long, and backed along its whole length by an expanse of dune sand, comprising the Reen, Gear, and Penhale sands which stretch back over a mile from the shore. In modern times the movement of dune sand has been much restricted by the spread of marram grass, but at the north-eastern edge opposite the hamlets of Ellenglaze and Trebisken the sand still moves forward, reaching the bed of a small stream which flows into Holywell Bay. Much of the sand appears to be carried by this stream down into the bay, behind which again lies a large tract of blown sand, continuous near the shore with the Penhale sands. Samples of the Holywell Bay and dune sand were therefore also included for study.

The Perranporth samples were collected on the shore and at various points on the dunes. These points were easily fixed on the map by taking prismatic compass bearings on a number of prominent chimneys at the deserted mines whose position is marked on the 6 in. geological survey map of the district (Wheal Vlow head gear is now dismantled). The sketch map (Text-fig. 1) indicates roughly the topography of the locality, the extent of the dunes, and the points from which samples were obtained. Samples P_0 to P_6 and Go_{25} were collected in September 1929, the Holywell samples in September 1930, and the remainder in 1932.

Perran Bay is enclosed at both ends by promontories projecting into deep water, Cligga Head on the south and Penhale Point on the north, which presumably preclude any along-shore movement of sand into the bay from either south or north. So it appears that, besides shell fragments from the sea floor, the available material for sand formation comes from the Killas composing the cliffs, and from the waste of the tin, copper, and silver mines, which though now closed down, were once active in this district. This mine waste would reach the beach principally by the stream which flows out at Perranporth. It must also be noted that the Great Perran iron lode, on which Gravelhill and Mount mines were situated, reaches the shore at the north end of the beach.



Text-fig. 1.—Sketch map showing the distribution of the Perran sands. (Based upon the Ordnance Survey map, with the sanction of the Controller of H.M. Stationery Office.)

It seems certain that the beach has been the only source of the dune sand, which in historic times first buried the ancient Oratory of St. Piran and then St. Piran's Church—the original parish church of Perranzabuloe. The remains of both of these have since been uncovered by the onward movement of the sand.

Wheal Vlow and Wheal Ramoth cannot have contributed any appreciable amount of material considering the dune sands as a whole, and the waste from Penhale and Phoenix mines was delivered into Holywell bay.

EXPERIMENTAL PROCEDURE

The mechanical and chemical compositions and the heavy mineral content of each sample were determined. Some measurements of degree of rounding were also made.

(*a*) *Mechanical Composition*

A weighed portion of each sample was separated into a number of grades by means of an elutriator and sieves. For the elutriation a vessel was used of the type described by Boswell (1918, pp. 25, 26). Particles of a diameter greater than 0·5 mm. were removed by sieving previous to elutriation. The maximum grain diameter was determined approximately by measurement under the microscope on a sample of the coarsest grade. The sand in the elutriator was separated out into a number of grades, the finest consisting of particles of less than 0·12 mm. in diameter. Each of these grades was collected, dried, and weighed. Each grade was then further treated as described below. With regard to the accuracy of this process the present results confirm the statements of Boswell (1918, p. 27). In connection with the roundness measurements, a large number of determinations of grain diameter were made microscopically and it was found that the average *minimum* diameter of the grain lay within the grade size—but that the maximum diameter was greater than the grade size—as determined by elutriation, the explanation being that grains of quartz tend to be "flaky" and of course lie on the microscope slide in such a position as to show a maximum area. Where a grain is not spherical its minimum diameter will really not be measured at all under the microscope in the usual way as it will be vertical to the plane of the slide.

(*b*) *Chemical Composition*

A weighed portion of each sample was treated with dilute hydrochloric acid and the per cent loss in weight determined.

This is quoted in the results as per cent of calcium carbonate and of course really represents the proportion of shell fragments in the sand. In some cases the iron in the acid extract was determined by a dichromate titration and the results calculated as Fe_2O_3. In addition each grade from the sieve or elutriator was treated separately with dilute hydrochloric acid, dried and weighed, in order to determine the distribution of shell fragments over the various grades. After this last treatment a sample of each grade was mounted up permanently on a slide with canada balsam for examination under the microscope.

(*c*) *Heavy Mineral Content*

An acid-washed portion of each sample was treated with bromoform in the usual way and the heavy mineral residue washed, dried, and weighed. Precautions were taken to make the separation as complete as possible and to avoid the disturbing effects of convection currents in the bromoform. In many cases duplicate determinations were made. The heavy mineral residues have been preserved for future study.

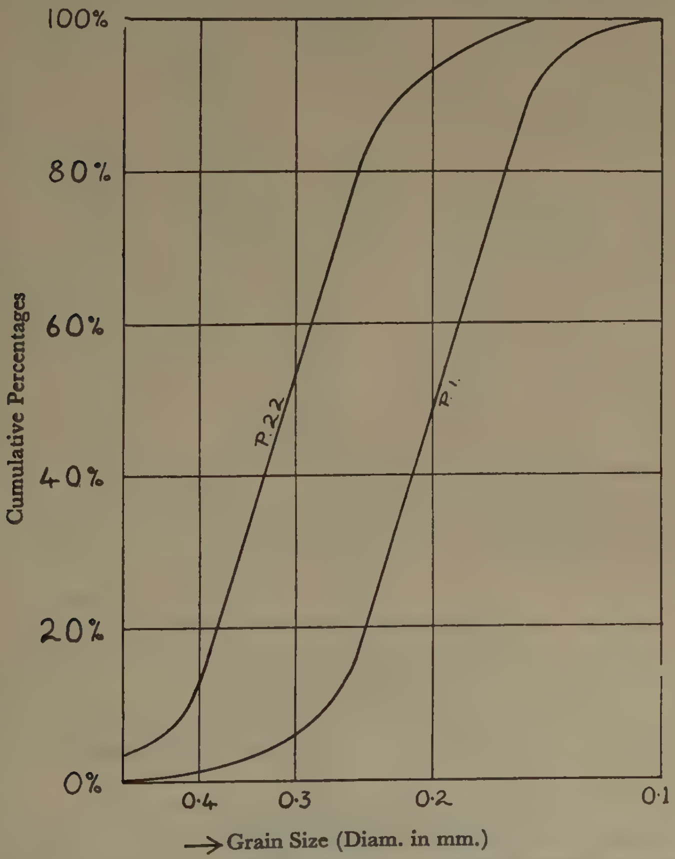
(*d*) *Roundness Factor of Grains* (*Sphericity*)

The degree of rounding of the quartz grains in a number of these samples was measured.

For this purpose the grain-circle method described by Tickell (1931, p. 6) was adopted. In this method the roundness factor is the ratio of the area of the grain (as seen on a slide) to the area of the smallest circle which will just circumscribe it. The diameter of this circle is commonly the maximum diameter of the grain. Tickell's grain-circle roundness factor is now described by the American school of sedimentary petrologists as " sphericity ".

A slide of the grade under examination was placed on the stage of a microscope arranged with a pointolite lamp for projecting images of the grains on to a large sheet of paper. The outlines of the grains were drawn on the paper and the projection of a stage micrometer scale added to give the degree of magnification. On the drawings the grain area was measured by a planimeter and the maximum and minimum diameters determined. It is to these diameter measurements that reference was made on p. 385. The roundness factor depends to some extent on the material. For this reason quartz grains only were used and measured. The shape of the grain also makes a considerable difference. If grains of square or rectangular section respectively underwent the same amount of rounding, the roundness factor for the square grain would be nearer unity than that for the rectangular grain.

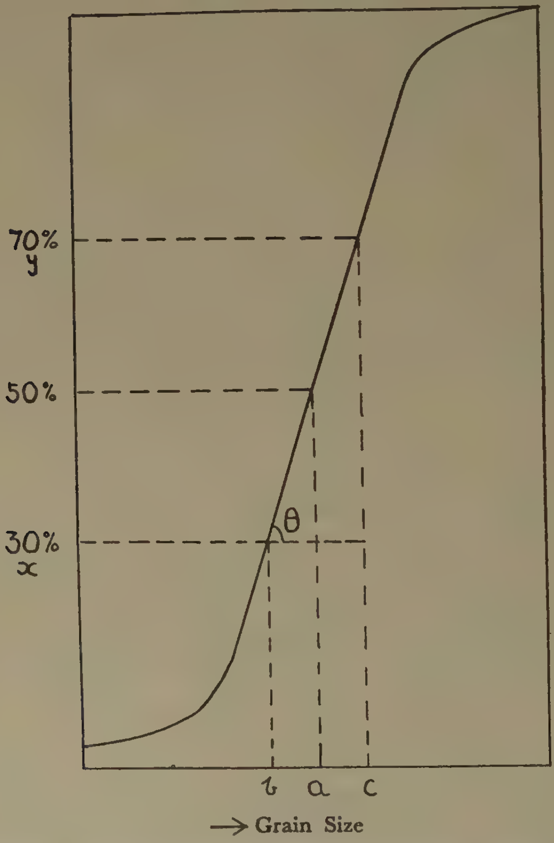
This effect is, of course, partly eliminated by measuring a large number of grains chosen at random. All the quartz grains projected from two positions of the slide taken at random were used. Roundness measurements were made on a shore sample and three dune samples from Perranporth.



TEXT-FIG. 2.—The two extreme cumulative curves for Perran sand samples.

Interpretation of Results

The results of the mechanical composition experiments were first expressed graphically, cumulative percentages (i.e. per cent wt. of grains above a given grade size) being plotted against the logarithm of the grade size. Two such curves are shown in Text-fig. 2, these being the two extreme curves for all the samples examined and typical of all the curves.



Text-fig. 3.—Calculation of 50 per cent grade and grading factor.

To facilitate the comparison of results two different figures were obtained from the graph. First the grade size for 50 per cent by weight of the sand (referred to subsequently as the 50 per cent grade) was read off. This value corresponds to the median of the American sedimentary petrologists (Krumbein and Pettijohn, 1938). Then the slope of the straight centre portion of the curve was determined. The actual value for the slope of the curve was divided by 100 to get figures of a more reasonable magnitude. In Text-fig. 3 the 50 per cent grade will be a and the slope of the curve is tan θ.

$$\tan\theta = \frac{y - x}{(\log b - \log c)}$$ since the grade scale is logarithmic.

The slope actually quoted in the results as grading factor is given by the formula $\frac{y - x}{100\ (\log b - \log c)}$. Cumulative per cent—log grade size curves were drawn both for the original and for the acid-washed sample. From these curves the 50 per cent grade and the grading factor were determined. These results are shown in Table 1.

For all the Perranporth samples the 50 per cent grade is practically the same before and after acid treatment. Differences in the grading factors of the original and acid washed sands are, however, definite and the significance of these differences will be discussed in connection with the chemical composition.

For some samples the grading factor is not quoted, either because there was some indefiniteness in the curve, or because the centre portion of the curve was not a straight line, or approximately so, between 30 per cent and 70 per cent, which were the values taken for x and y in evaluating the grading factor. An inflexion of this type in the curve may point to a mingling of sands from two different sources. For instance sample P_7 taken in the neighbourhood of the mine burrows of Wheal Ramoth may have received some additions from those burrows.

The grading factor gives a measure of how well the sand has been sorted out. If the diameter of most of the grains in a sample lie between narrow limits the curve is steep and the grading factor high. It may be noted that the grading factors of the beach sands are, on the whole, higher than those of the dune sands, pointing to the greater sorting efficiency of water action. The grading factor of the shore samples rises on proceeding in a northerly direction up the beach.

The distance from the shore is measured in a S.W.–N.E. direction in the case of dune samples. This proceeding is based on the assumption that the prevailing wind comes from the S.W. and that this direction is therefore the direction of maximum travel of the sand grains. This assumption is borne out by the disposition of the dunes, their greatest inland penetration being towards the N.E.

The results for the proportion of the shell fragments in the various samples are interesting. The total percentage only varies between fairly narrow limits—49 to 57 per cent for shore and 50 to 62 per cent for dune sands. The greater percentage in the dune sand is to be expected as the shape of the shell fragments render them rather more easily lifted and therefore more easily transported than the quartz grains. The results are given in Table 2, and the iron content, where determined, is also shown. The most interesting figures, however, are those for the distribution of shell fragments over the various grades.

TABLE I

MECHANICAL COMPOSITION, HEAVY MINERAL CONTENT, AND LOCATION OF SAMPLES

	Sample number	50 per cent grade (original)	50 per cent grade (acid washed)	grading factor (original)	grading factor (acid washed)	Distance from shore. Yds.	Per cent of heavy minerals	Notes
SHORE	P. 21	0·27	0·27	8·8	8·3	—	—	440 yds. N. of P.
	P. 22	0·31	0·33	3·4	2·8	—	—	440 yds. N. of P.
	P. 23	—	0·37	—	3·5	—	—	900 yds. N. of P. near Wheal V adit.
	P. 25	0·26	0·26	6·4	5·5	—	—	440 yds. N. of P.
	P. 26	0·28	0·27	3·2	3·4	—	—	S. end near Cha Rock.
	P. 0	0·22	0·22	4·1	3·6	—	2·2	200 yds. W. Chapel Rock.
DUNE	P. 1	0·20	0·19	3·2	3·4	10	6·3	
	P. 2	0·20	0·20	3·2	3·2	100	4·4	
	P. 3	0·22	0·21	3·3	3·1	180	2·0	
	P. 4	0·21	0·21	3·9	3·3	270	2·4	
	P. 5	0·21	0·21	3·0	2·8	370	2·1	
	P. 6	0·22	0·22	3·2	3·0	460	2·4	
	P. 7	0·20	0·20	—	—	550	1·8	in neighbourho of Wheal Ram old mine burr
	P. 8	0·22	0·22	4·1	3·7	640	3·2	
	P. 11	0·25	0·26	3·0	2·7	430	0·81	
	P. 12	0·26	0·26	3·2	2·7	860	0·97	
	P. 13	0·30	0·32	3·7	2·7	1,470	0·66	near St. Piran Oratory.
	Go. 25	0·26	0·27	4·4	3·9	2,090	0·75	near St. Pirans Church.
	P. 14	0·26	0·27	3·4	2·6	1,870	0·71	
	P. 15	0·23	0·22	3·0	2·7	2,210	0·43	
	P. 16	0·26	0·27	3·5	2·8	2,620	0·45	
	P.L. 3	0·28	0·29	4·4	3·8	940	0·5	
	P.L. 4	0·24	0·23	3·8	3·5	1,550	1·3	near Ellenglaze
	P.L. 15*a*	0·27	0·27	5·9	4·9	530	0·17	Samples taken same point top, middle bottom of dune slope.
	b	0·26	0·26	4·3	3·7			
	c	0·25	0·25	5·9	5·4			
	P.L. 18	0·32	0·32	—	—	1,960	0·2	
	P.L. 19	0·28	0·29	4·4	3·9	3,180	0·7	

In every case the percentage of shell is highest in either the 0·20–0·25 or the 0·25–0·30 mm. grade, and lower in both the finer and the coarser grades. The decrease in percentage in the coarser grades is easily explained by the greater fragility of a shell fragment as compared with a quartz grain. The lower percentage in the finer grades is less easy to explain unless the greater solubility in water of fine particles comes into play.

TABLE 2

COMPOSITION OF SAND SAMPLES.

Sample number	Per cent of calcium carbonate in grade						Total per cent of $CaCO_3$	Per cent of Fe_2O_3
	0·12–0·15	0·15–0·20	0·20–0·25	0·25–0·30	0·30–0·50	0·50 →		
P. 21	38	46	57	58	48	36	55·7	—
P. 22	—	51	58	58	42	44	48·9	—
P. 25	—	45	55	55	34	—	51·9	—
P. 26	37	37	48	43	57	46	49·5	—
P. 0	43	56	60	54	52	—	57·2	0·46
P. 1	35	50	59	53	44	—	52·8	0·76
P. 2	37	47	58	53	45	—	52·0	0·65
P. 3	38	54	59	60	53	—	55·3	0·27
P. 4	40	52	62	59	53	—	56·2	0·45
P. 5	40	55	63	58	47	—	56·0	0·45
P. 6	37	55	62	62	52	—	58·1	0·38
P. 7	—	54	59	55	51	—	55·3	0·34
P. 8	42	53	62	61	58	—	58·3	0·67
P. 11	40	53	60	58	43	31	53·1	—
P. 12	41	57	69	65	52	—	59·6	—
P. 13	40	54	59	58	43	—	50·5	—
Go. 25	42	57	61	59	45	—	55·0	0·33
P. 14	40	57	63	62	49	—	58·1	—
P. 15	40	52	59	58	46	—	53·6	—
P. 16	43	56	61	60	43	36	53·4	—
P.L. 3	47	53	59	62	50	48	56·9	—
P.L. 4	50	52	62	65	56	—	60·4	—
P.L. 15*a*	39	52	60	64	46	47	57·7	—
b	35	51	61	64	53	40	58·1	—
c	35	53	61	66	61	—	62·2	—
P.L. 18	42	55	61	63	49	61	54·4	—
P.L. 19	—	54	61	65	56	50	59·9	—

In the case of gypsum it has been shown (Hulett, 1901, 1902) that the solubility of the finely divided material is appreciably greater than that of the coarse-grained solid and it seems likely that the same should be true for calcium carbonate.

The distribution of heavy minerals shows some points of interest. As was pointed out in a previous paper (Barrett, 1930) the action of the wind on dune sands seems to be to transport the light grains more easily than the heavy minerals. Of the samples examined, P_1 to P_8 were taken at regular intervals up a long sandy slope, leading from the shore to the top of the dunes, P_1 being nearest to the shore (near H.W.M.), and P_8 on the top of the dunes. It will be seen that there is a fairly steady drop in the percentage of heavy minerals except for the sample P_8. This sample was found by plotting on the 6 in. map, to be taken from near a concealed mineburrow of the old deserted Wheal Ramoth mine, and may consequently have received some local enrichment of heavy mineral. Samples No. P_{11}–P_{16} were taken along a line at right angles to the shore and show also a tendency for heavy mineral to decrease. The grading action of the wind, when not obscured by the other factors, is best seen from the results for Holywell Bay sand (Table 3). The samples No. 1 to No. 6 were taken up a smooth dune slope early one morning after a night of high wind before the sand had been disturbed. They show not only a steady drop in heavy mineral content, but also a steady drop in grading factor—suggesting that high degree of grading is due to water action, and that wind transport tends to be less selective.

TABLE 3

HOLYWELL BAY SANDS.

Sample number	50 per cent. grade	Grading factor	Per cent of $CaCO_3$	Per cent of Fe_2O_3	Per cent of heavy mineral	Notes
Go. 17	0·26	4·8	62·9	1·1	0·24	SHORE.
H. 1	0·32	8·6	57·8	0·96	0·38	DUNE SLOPE.
H. 2	0·29	7·9	63·1	0·96	0·34	
H. 3	0·27	5·5	63·1	0·96	0·33	
H. 4	0·27	5·0	62·2	0·86	0·30	
H. 5	0·26	4·9	64·1	0·98	0·25	
H. 6	0·24	4·0	61·8	1·12	lost	
Go. 104	0·25	3·9	63·3	0·80	0·67	TOP OF DUNES.

Finally the degree of rounding or sphericity of the grains from each sample show some points of interest. These results are given in Table 4. Four samples were chosen for these measurements—a shore sample P_0 and three dune samples, P_1, P_6, and Go_{25}.

By this method of measurement the sphericity of a perfect cube would be 0·64. Therefore it appears possible from the figures in Table 4 that particles below about 0·20 mm. in diameter have not been appreciably rounded by water action though the results are too scanty for a definite conclusion to be drawn on this point. It does appear probable, however, that the sphericity begins to increase in proportion to the distance the sand has travelled, and must be therefore directly due to wind action.

TABLE 4

RESULTS OF SPHERICITY MEASUREMENTS

Sample number	Sphericity of sand of grades :—						Distance from shore
	→0·12	0·12–0·15	0·15–0·20	0·20–0·25	0·25–0·30	0·30–0·50	
P. 0	0·61	0·65	0·67	0·72	0·70	0·67	shore
P. 1	—	0·66	0·72	0·75	0·67	0·69	10 yds.
P. 6	—	0·72	0·73	0·76	0·71	0·71	440 yds.
Go. 25	0·71	0·78	0·78	0·73	0·76	0·72	2090 yds.

Further experiments on artificially produced rounding of quartz grains are in progress in the hope of throwing more light on this problem.

The thanks of the author are due to Mr. C. L. Bryant for providing him with some of the samples.

SUMMARY

To sum up, we may say that the foregoing experiments indicate that—

(*a*) The 50 per cent grade of all samples from this locality only varies between narrow limits ;

(*b*) The high degree of grading (as expressed by grading factor) of the samples is due to water action rather than to wind action ;

(*c*) Heavy mineral grains are more readily left behind during wind transport than quartz and shell fragments ;

(*d*) Sand grains of diameter less than 0·20 mm. are probably not rounded by water action, and the rounding of sand grains up to 0·5 mm. diameter by water is only slight. Short wind transport begins to cause incipient rounding of sand grains, and this degree of rounding bears some relation to the distance the sand has been transported ;

(*e*) Shell fragments appear to accumulate in the medium grades of a sand, the coarser and finer grades containing less than the average percentage of calcium carbonate. It is suggested that the explanation of this may lie in the greater fragility of shell fragments and in the greater solubility in water of the finer particles.

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An Hypothesis of Submarine Canyons

By Alex. L. du Toit, Johannesburg

Introduction

THE publication by the Geological Society of America of that momentous work by the late A. C. Veatch and P. A. Smith (1939) with its beautifully executed charts, following closely Douglas Johnson's stimulating contribution on the subject (1938), again focuses attention on those stupendous erosion-features—the " Submarine Canyons ". Through stressing the relatively brief space of time available for their evolution, this latest pronouncement only renders more of an enigma those gigantic furrows that would now seem to fringe so much of the continental margins. As Daly has remarked (1936, p. 402), they appear to be planetary and not merely regional. It is in the Atlantic, however, that they have been most thoroughly studied.

It is not unlikely that, had scientists, without previous knowledge of the subject, been asked whether such channelled plateaux could exist beneath the ocean, they would almost unanimously have derided such suggestion, and doubtless have submitted arguments against such fantastic ideas. To-day the actuality of the Submarine Canyons savours almost of a colossal joke on the part of Nature, one which human ingenuity is nevertheless endeavouring to interpret.

Johnson (1938, p. 112) has pointed out that similar, though genetically distinct, forms are probably being classed together, though their discrimination is not yet possible, all having for the present to be termed " submarine canyons ".

Notching the Continental Shelf, they are cut back into that plateau, for miles in places, though only occasionally do they cross the shelf to join with existing river channels, as in that of the Hudson or Congo River. Ranging from a few up to ten miles in width and expanding in their lower sections, they may receive one or more short tributaries in their upper parts. They descend abruptly from the shelf and are traceable to depths exceeding 1,000 fathoms frequently, and 1,400 fathoms in certain cases, with gradients varying from 1 to nearly 6 per cent, and hence very much more steeply than normal rivers. Their cross-sections are V-shaped and they flare with depth, while their slopes are in places steeper than the angle of repose for unconsolidated materials. In such spots they must be bounded by rocky ledges, but the gentler slopes and the bottoms are mostly covered by mud.

Off the eastern United States the canyons are spaced somewhat unevenly, but are, through the medium of clearly transitional types, intimately connected with the more extensive and regular furrowing of the Continental Slope, which seems to be most closely patterned off the coasts of Maryland and Virginia. The Slope itself is inclined at between $\frac{3}{4}$ and 2 per cent generally, though steeper in places.

Strikingly, while the canyons are traceable to the amazing depths of 6,000, 7,000 or even 9,000 feet, the actual incisions that they make in the Slope are commonly less than 400 fathoms deep, to reach a maximum of 600 fathoms in the case of the Hudson. If a terrestrial origin for these chasms be conceded, then the limit of some 4,000 feet will be set to the former optimum elevation of the Continental Rim.

SUBMARINE VERSUS SUBAERIAL ORIGIN

It is universally admitted that, so far as is yet known, the canyons show in their detail all the peculiarities of normal terrestrial ravines, and such applies even more markedly to the associated furrowing. This is finely brought out in the charts by Veatch and Smith, although the particular type of topography there depicted is admitted by them to be not the only possible one, and more numerous and closer-set soundings may demand some modifications in contouring. These writers are nevertheless correct in emphasizing the stream-like erosion-pattern over the slope and also its terrestrial likeness. Such natural interpretation, which was indeed advocated for the Hudson Canyon so many years ago by Lindekohl and Dana, finds serious opposition, however, in the vast lowering of ocean-level that would be demanded, and with it the related problem—only one among other serious difficulties—of the temporary disposal of the displaced oceanic waters.

To evade such stupendous and rather improbable mechanism several hypotheses have been formulated that presume subaqueous erosion effected by currents, sapping, slumping, mud-sliding, etc. The small current velocities actually measured by Stetson (1937) along canyon-floors of George's Bank, south-east of Long Island—up to one-fourth of a mile per hour—would seem to rule out the first-named agency, though such speeds might yet be enough to keep the ravines free of silt. Whether the velocities would become sufficiently intensified by strong turbidity, as calculated by Daly (1936) and Kuenen (1938), must await confirmation through further measurements, especially along the middle and lower reaches of the canyons. The discovery of ravines possessing steep walls of fairly consolidated materials such as sandstone, or even of crystalline rocks, as recorded by Shepard (1936) and Andrade (1937), raises strong doubts concerning the ability of even heavily silt-charged currents to excavate such immense chasms beneath the ocean, and furthermore to such depths, where gradients have incidentally become much flatter.

Johnson (1938, pp. 233–156; 213–133) has argued at length and almost convincingly for the importance of sapping through submarine springs and still more through the expulsion of the contained water from the porous sediments held to build the continental slope. If such sapping, or alternatively, if turbidity currents, were as potent as argued, such an action should also have operated in the past under more or less similar conditions. Now numerous cases of marine fringing-sediments of Mesozoic and Tertiary age, like those presumed to build the Atlantic Shelf and Slope, have been upheaved for inspection in various parts of the world. It is for stratigraphers to advise whether among such comparable profiles there is any clear example of an intensely dissected surface of dendritic pattern with high relief preserved beneath a younger, and preferably marine, covering.

While it is readily conceded that submarine agencies could have contributed materially to the development or maintenance of the ravines, the view that such agencies were primarily responsible for their initiation and excavation seems too large an order. Consequently, however improbable at first sight it might appear, we are thrown back upon the original suggestion, that of *subaerial erosion*. Even Johnson, protagonist of sapping processes, admits that a subaerial origin is still a working hypothesis. At the same time we shall have to rid our minds of the commonly expressed or implied idea that land, shelf and slope have throughout moved undeformed as a unit in relation to the ocean. On the contrary we shall be driven to recognize differential movements within the continental border. Movements of the kind producing Graben can generally be discounted, although in certain cases notching was definitely controlled by fault-systems trending normal or oblique to the shore, as detailed for the coast of Portugal by Andrade (1937, pp. 179–184).

A scheme involving both faulting and warping with trends more or less parallel to the continental margin would appear more promising, as was suggested by the author in 1937 (p. 226), developed further when dealing with the presumed " rift-basin " of the Atlantic–Arctic Ocean (1938, p. 146). This, the *Orogenic Hypothesis*, is elaborated below with proper recognition given to some of its weaknesses.

STAGES UNDER THE OROGENIC HYPOTHESIS

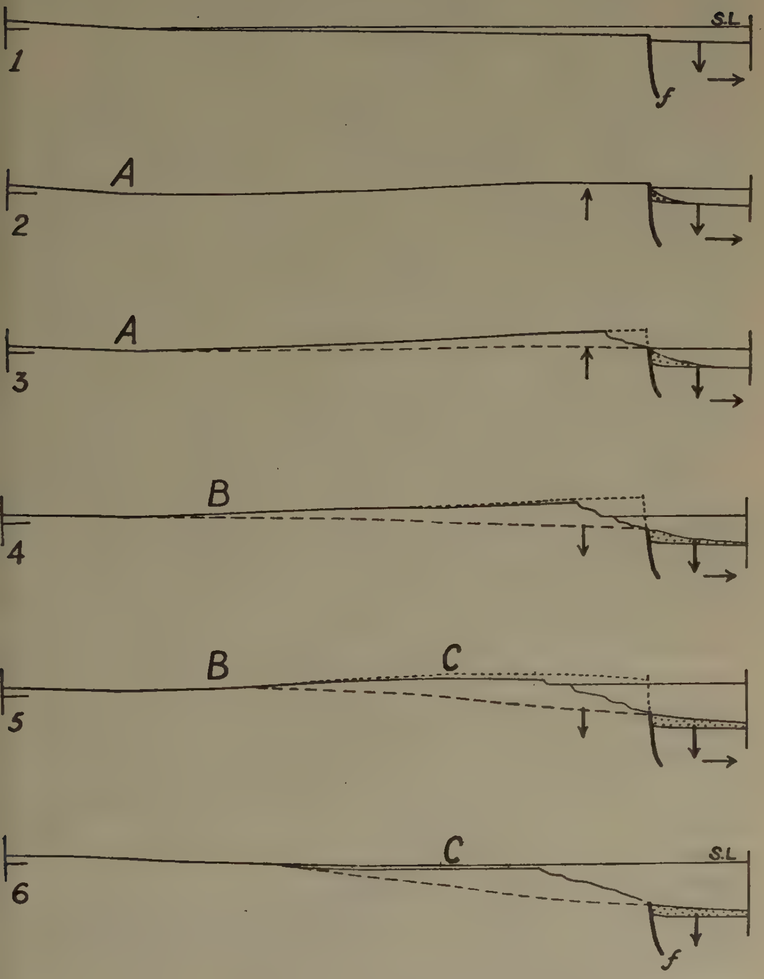
The scheme is pictured in Text-figs. 1–6 for a coast of the " Atlantic Type " off which strong marginal faulting under regional tension is assumed. The mobile zone is regarded as having a width of between 25 and 150 miles—comparable, therefore, with the thickness of the crust involved.

In Text-fig. 1 a series of Tertiary (and older) fringing sediments inclined faintly seawards becomes faulted, only a single fracture being indicated, though multiple faulting can alternatively be postulated. As the writer has shown elsewhere (1937, p. 250), such abyssal faulting will, through the virtual thinning of the Sial, cause one side of the fault-block to rise in accordance with isostatic and paramorphic principles—a phenomenon termed " pseudo-arching ", which is characteristic of major " rift valleys ". Down-dragging of the continental rim by the subsiding ocean floor is hindered by slipping along the fault plane or planes.

In Text-fig. 2 the rim consequently bends upwards about the hinge-line A and appears above the waves, while the larger rivers draining the mainland become prolonged across it and proceed to cut their channels through the newly-formed coastal barrier.

Text-fig. 3 exhibits the continued rise of this rim on which a consequent drainage system, directed *inland*, develops, while the major rivers maintain their courses in deepening gorges conspicuously lacking in tributaries. Waste delivered by them or derived from the eroding rim becomes spread over the ocean floor in a series of overlapping fans, that are worked over by the waves and that help to bury the fault-scarp or scarps.

In Text-fig. 4 pseudo-arching reaches its maximum—according to our estimates not more than about 4,000 feet, which will give an internal dip-slope of between ½ and 2 per cent—slipping along the master fault ceases and the subaerial canyons attain their greatest depths—2,000 to 3,600 feet—while dissection of



Text-figs. 1–6.—Hypothetical stages in the Evolution of a Submarine Canyon; the broken line indicates the] Canyon Floor.

the coast becomes most active with incision of its seaward-trending sub-parallel drainage. Continued or renewed tension causes further sagging of the ocean floor with down-dragging of the rim, an action clearly revealed by those numerous instances of seaward-tilted, marine-cut, coastal peneplains, for example around the southern end of Africa.

Text-fig. 5 displays such downwarping, about a hinge-line B (which may or may not be coincident with A) with progressive marine erosion of the sinking furrowed coast and the drowning of its canyons. Such downwarping stands revealed by the present profiles of the canyon floors, which commonly show a monoclinal inflection, as at C. In the case of the Hudson canyon this is situated at 525 fathoms. Off the eastern United States the axis of such inflection upon proceeding from N.E. to S.W. transgresses well on to the Shelf; to the N.W. of that axis the canyon profiles are convex, to the S.E. concave (see figs. 5 and 6).

Text-fig. 6 exhibits the continuance of such downwarping causing the outer portion of the now submerged landscape to dip at between 1 and 4 per cent and thereby constitute the Continental Slope, while the inner portion becomes transsected by a plain of dominantly marine abrasion to form the Continental Shelf. Cogent arguments for the surf-cut nature of the shelf are given by Veatch. In most cases that surface becomes cut right across or even below the tilted canyon floor, so that the inner section of the ravine is severed from the parent river. The Hudson and Congo have, however, maintained their channels across the shelf. In other and presumably smaller examples the gullies traversing the shelf may, as suggested by Veatch, become filled with waste from the cutting of the shelf or with glacial debris and so obliterated. Over the Slope silt will accumulate, essentially upon the ridges and divides, since springs and turbidity streams will tend to keep the furrows cleared. To the very considerable downwarping are due the abnormally steep canyon-gradients.

The above is merely an outline, since the details would, as under any hypothesis, have varied appreciably according to local conditions. In certain areas again the phenomena would have been feebly developed or absent.

While the foregoing will apply to supposed tension-basins, the existence of canyons off the Pacific coasts of North America and Japan proves their development in compressional regions as well. One can readily conceive, however, of the flexing and upheaval of a coastal or offshore barrier zone, of its transsection by subaerially-cut ravines and of its subsequent depression and planation. Whether there would result a physiographical distinction from the tensional variety sufficient to establish a separate genetic type must await further investigation.

CONSEQUENCES OF THE ABOVE HYPOTHESIS

It is frankly admitted that such conjectured elevation of the continental rim, to perhaps as much as 4,000 feet in places, with its subsequent downwarping and transsection puts much strain on credulity. If its probability be denied, then it is hard to see how the canyons could have been cut subaerially unless a vast sinking of the ocean floor had occurred, say beneath the Pacific, dropping sea-level by 8,000 or even 9,000 feet, with almost precise restoration after the relatively brief period occupied in canyon-cutting—which all seems too far fetched.

Under the hypothesis propounded one can anticipate with such an elevated rim evidence pointing to :—

(*a*) sediments, swept *landwards* from the rim, preserved in the existing youthful coastal formations and/or terrestrial phases passing below sea-level. On those points stratigraphers can report favourably or adversely ;

(*b*) climatic changes, due to the influence of the rim itself. On the Atlantic side of southern Africa there is definite proof of relatively recent and appreciable changes in rainfall, winds and transportation of sand. In the eastern United States some of the phenomena attributed to the Pleistocene Ice can conceivably be due to such suggested cause ;

(*c*) close and regular furrowing of the outer slope independent of the canyons themselves, caused by higher precipitation on the seaward side. Daly (1936, p. 402) has indeed remarked that in the case of George's Bank such secondary furrows could scarcely have been kept fed by the drainage off the present bank, supposing the shelf emergent ;

(*d*) some deflection of the main rivers into courses oblique instead of normal to the coast. One can cite the direction of the Chesapeake river as well as those curious former drainages (not yet described) revealed by river-gravels trending nearly parallel to the shore in Namaqualand, South Africa ;

(*e*) erosion-benches along the face of the submerged continental slope, marking steps in its sinking. The published soundings off the United States are not sufficiently close together to establish that supposition definitely, since any apparent breaks of slope can equally well be ascribed to hard and soft layers, but a fairly persistent ledge is nevertheless suggested at between 900 and 950 fathoms and a sudden rise at between 600 and 650 fathoms. Studies of existing echometer records, taken along suitable profiles, ought to yield positive information on this point, more especially in the south-western area, where any glacial veneer will presumably be thinner ;

(*f*) because of the magnitude of the canyons submarine deltas should exist off their mouths, even under those hypotheses involving sapping and mud-flow. Yet there is an apparent absence of deltas, as admitted by Daly and Johnson ; even one for the colossal Congo trough has not yet been located. Under our view much of the detritus from the cutting of the canyons may be swept away by shore currents, while the coalescing fans off the minor furrows will help in the blotting out of such deltas and, incidentally, the fault-scarps as well ; minor irregularities will become levelled up by silting. Deltas can therefore be present although modified and not easily recognizable.

Other, though less important, implications of the orogenic hypothesis will readily suggest themselves to critics.

Comparison with other Hypotheses

In no small degree the views expounded resemble those recently and independently advanced by Veatch, a resemblance which will be increased were a monocline or a series of " knee-bends " to be substituted for the writer's master-fault or faults. Faced with no tangible evidence of peri-continental faulting, Veatch postulated a great coastal up-arching—resulting in canyon-incision—followed by greater marginal downwarping—making the Continental Slope—with final marine planation—producing the Shelf. Worked out skilfully and supported by many observations, particularly for the Congo region, his views are worthy of serious consideration. Matters would certainly be simplified if, with Veatch, the Slope could be regarded as a downwarped flattish arch traversed by terrestrially-cut drainages, but, as he himself admitted, the preceding phase of strong marginal up-arching remains a puzzle. How was it caused and why was it thus localized ? Was one of the predisposing factors perhaps the lenticular character of the fringing sedimentation ?

For those and other reasons the author had long previously been induced to seek an explanation in crustal tension and rupture and to connect it for the Atlantic and Indian oceans with the development of those basins through Continental Sliding. Such a mechanism will evidently be the same whether limited stretching of the ocean floor or full continental drift be conceded, save that in the former case any results on the scale observed could scarcely be expected.

Now, to explain the extraordinary seaward-facing escarpments and landward-directed peneplains and drainages within so much of the countries fronting the Atlantic, the author (1937, p. 256) had to postulate a similar *orogenic plus erosion cycle* during the Cretaceo-Tertiary, one which had to be connected furthermore with crústal tension and marginal faulting. In many respects the particular phenomena and their interpretation parallel those set forth for the canyons, save that in the former case the usually elevated and dissected fault-scarp with its river-cut transverse gorges has retreated to a position *inside* the hinge-line of subsequent downwarping and has so escaped submergence. The external surface of marine erosion is nevertheless preserved in the seaward-tilted coastal peneplain, which can analogously be viewed as a " fossil continental shelf ".

The presence in the Congo and Angola regions of not one, but a group of such interior peneplains and coastal shelves showing varying degrees of tilting and dissection, as pointed out by Veatch (1939, p. 35), Jessen (1936, p. 325) and Dixey (1938, p. 119), argues thus for a series of stretchings within the Atlantic Basin, to be in turn correlated with the Alpine Diastrophism. Similar evidence is available from the eastern United States.

There are accordingly grounds for concluding that periodic tension operating from the late Mesozoic onwards has been essentially responsible for the sequence of coastal faultings, uptiltings and downwarpings along the margins of much of the Atlantic and Indian oceans, of which the Submarine Canyons appear to constitute almost the latest phase. The suggestion of a Pleistocene Age, or one even more youthful in the case of the Congo, as convincingly argued by Veatch (1939, pp. 25–31), is remarkable in that it will crowd such vast crustal movement and erosion into so brief a span.

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Some Lower Palaeozoic Contacts in Pembrokeshire

By Professor O. T. Jones

DURING the excursion of the Sedgwick Club to Pembrokeshire at Easter this year the junctions between certain of the rock groups were examined under unusually favourable conditions with interesting results.

Solva-Caerfai contact.—The junction between the Solva and Caerfai groups is well exposed on the east side of Caerfai Bay, but at ordinary tides it can only be reached some way up the cliff. The mutual relations of these groups acquired new interest when the Ford beds which were suspected to be of Upper Solva or Menevian age were found to rest unconformably upon Caerfai Beds, in the Hayscastle district.[1] At that time no fossils had been found in the Ford Beds in spite of repeated search in the material from the long railway cutting near Ford. During the previous visit of the Sedgwick Club at Easter, 1932, Mr. T. C. Nicholas and others were fortunate enough to find several fossils on the platform at the station opposite Ford.[2] These fossils proved to belong to the Zone of *Paradoxides hicksi*; in view of the similarity in the lithology of all the Ford Beds it is considered likely that they belong to this zone down to the Musland grits which form their base. The Solva beds are therefore absent in that locality and they have either been overstepped or overlapped between St. Davids and Hayscastle.

The Caerbwdy sandstones which form the uppermost beds of the Caerfai Group are dull purple muddy sandstones; on the east side of the bay they are succeeded just north of the great strike-fault which traverses the headlands by coarse pebbly greenish sandstones. The junction is exceedingly sharp and might be a nonsequence of considerable magnitude. In spite of some movement near the junction, the contact in most places is not faulted. The beds descend almost vertically from the top of the cliff, and this year owing to the exceptionally low tide it was possible to gain access to the contact near the base of the cliff. It is exposed near the level of the sands a few yards north of the cave eroded along the strike-fault.

The base of the Solva group comes down in a straight line to within a few feet of the shore and is then offset several feet nearly horizontally before dropping to the level of the sand.

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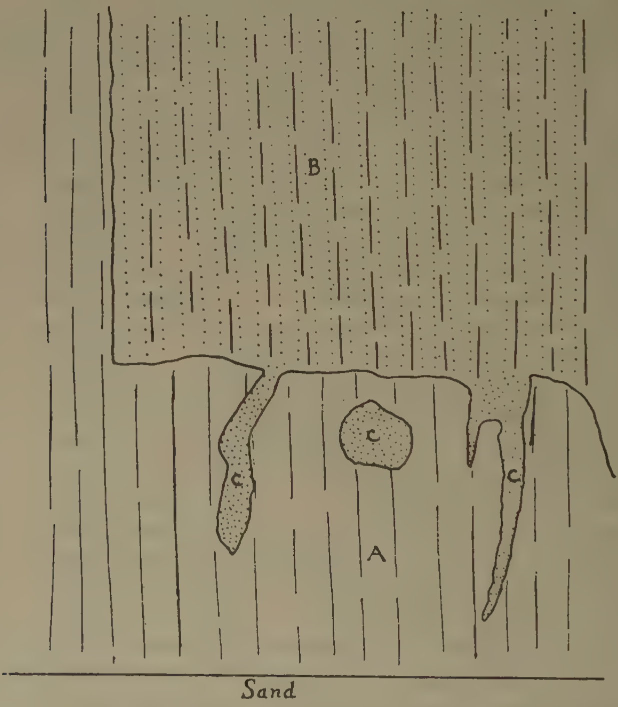
[1] H. H. Thomas and O. T. Jones, *Quart. Journ. Geol. Soc.*, lxviii, 1912, 393.

[2] *Geol. Mag.*, lxx, 1933, 383.

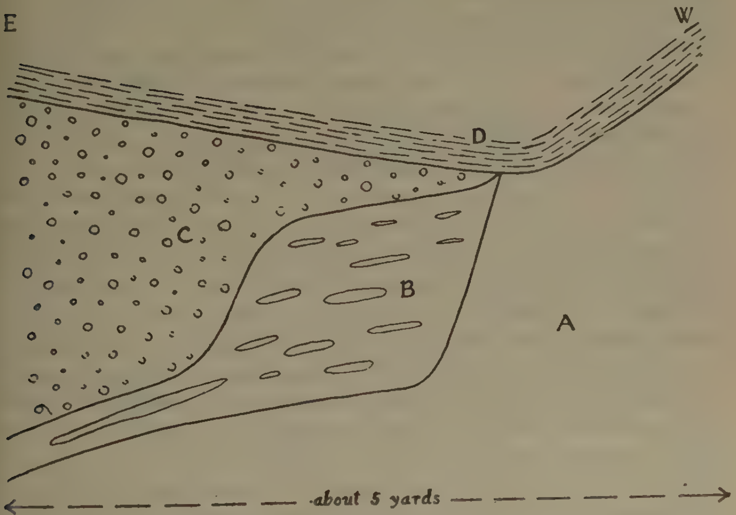
In the horizontal portion the greenish sandstones penetrate into fissures in the purple sandstones, and one pocket is completely surrounded by the purple beds (see Text-fig. 1).

It is obvious that the Solva beds were deposited on an uneven surface of Caerfai beds which descended several feet in one step and the sands entered into crevices and holes in the face of the step. There is little doubt, therefore, that an unconformity of some magnitude separates the Solva from the Caerfai group at this locality. In the Hayscastle district about 100 feet of green quartzitic sandstones and shales overlie the Caerbwdy sandstones. Since the unconformity at Caerfai appears to be at the base of the Solva it is not unlikely that the green beds at Hayscastle are a higher part of the Caerfai group not represented at the type locality.



TEXT-FIG. 1.—Junction of the Caerfai and Solva Groups in Caerfai Bay. The sketch is partly diagrammatic, since conditions did not allow of accurate measurements. A, Purple Caerbwdy sandstones (Caerfai Group); B, Greenish pebbly sandstones (Solva Group); C, infillings of B in A.

Arenig-Lingula Flags Junction.—On the north side of Whitesand Bay a narrow promontory called Trwyn-Hwrddyn separates the Tetragraptus Shales in Porth Lleuog from the Lingula Flags which occupy the north side of the bay. After the discovery of the striking unconformity between the Arenig and the Lingula Flags on Ramsey Island by members of the Geologists' Association on 30th July, 1930, the junction between these two formations on Trwyn Hwrddyn was examined a few days later. "Examination in the light gained on Ramsey Island revealed the fact that the Ordovician Beds begin in places with a thin layer of conglomerate, but the junction is so disturbed by a complex of little strike-faults accompanied by quartz veins that from this section alone it would be impossible to say that any unconformity between the Formations existed. The line of junction is still further obscured by remnants of a raised beach débris which adheres to the platform."[1]



TEXT-FIG. 2.—Junction of Arenig beds with Lingula Flags in Whitesand Bay. D, streaky sandy mudstones of Porth Gain type (Arenig); C, boulder conglomerate with coarse sandy matrix (Arenig); B, sandy matrix resembling C, with slabs of Lingula Flags, diagrammatically represented (Arenig); A, Lingula Flags.

The contact is difficult to follow along the promontory; in the attempt to trace it Mr. Fitzgerald Moore discovered a coarse conglomerate just above the sand at a point which is only accessible at low states of the tide.

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[1] *Proc. Geol. Assoc.*, xli, 1930, 431.

The inland end of the section is in line with the outer two of three large boulders lying in the middle of Porth Lleuog bay. The section is about five yards in length, and is cut off on the south by a strike fault which brings the Arenig beds of the section against Lingula Flags.

At the top of the section are a few feet of streaky sandy mudstones similar to the Porth Gain beds described by Professor A. H. Cox, and to those that occur below the Tetragraptus Shales on the south side of Porth Lleuog (see Text-fig. 2). These beds dip northward and overhang slightly the lower part of the section. At the east or inland end the streaky beds are underlain by the above-mentioned conglomerate containing boulders up to eight inches in diameter set in a matrix of the same type as the material of the overlying beds but coarser. In the middle of the section the conglomerate is underlain by a lenticular bed of peculiar composition which rests upon the Lingula Flags. This bed contains large pieces of Lingula Flags, one of them being a flat slab only a few inches thick. These are included in a matrix similar to that of the conglomerate; it is the kind of material that might be found at the foot of a cliff and undoubtedly belongs to the Arenig period. At the west or seaward end of the section the conglomerate and the underlying "scree-bed" are overlapped by the streaky mudstones which there rest directly upon the Lingula Flags. In view of the local occurrence of these basement beds their preservation in this one place is a fortunate circumstance.

The junction between the Llandeilo and Llanvirn in Abereiddy Bay.—The Llandeilo rocks are represented in Abereiddy Bay by dark calcareous shales yielding occasional trilobites and graptolites. They weather to a light ashy-brown colour at the top of the cliff and in these and other respects they compare closely with the Hendre Shales which the officers of the Geological Survey proved to replace the typical Llandeilo Limestone formation in West Carmarthenshire and Pembrokeshire.

It seems to have been generally assumed that these shales rest conformably on the highly fossiliferous Llanvirn shales in the south-east angle of the bay from which innumerable specimens of *Didymograptus murchisoni* and allied forms have been obtained by collectors.

Incidentally most of the slaty slabs from which the majority of collectors obtained fossils have been washed out during recent storms and the former hunting ground is now almost denuded.

The slabs are scattered along the whole length of the storm-beach which lies across the middle of the bay.

When the contact is carefully examined on the foreshore and in the cliffs it proves to be disappointing. On the foreshore the rocks on both sides of the junction are greatly shattered and veined and no original contact can be found. In the cliff, evidence of movement is less obvious ; nevertheless the rocks along the junction are slickensided and veined, and it is certain that the present condition is the result of shearing which has destroyed the original relations whatever they may have been. The two rocks are, however, undoubtedly conformable in dip for a thin band of ashy shale can be traced all the way up the cliff always maintaining the same distance of about two feet below the junction. At the same time there is no suggestion of a lithological passage or transition between the two rock groups. The lowest beds of the Llandeilo are coarser and much more sandy than the higher beds in the centre of the bay. They are reminiscent of basement beds and may well indicate that the original contact was a nonsequence if not an unconformity. In other parts of South Wales, notably at Llandeilo and near Narberth, where the Llandeilo Limestone prevails, that limestone rests directly upon the Lower Llanvirn (*Didymograptus bifidus*) shales and the *Didymograptus murchisoni* beds are absent ; near Narberth a typical rubbly basement bed occurs below the limestone.

As Abereiddy Bay appears to be the only locality where the junction between the Hendre Shales and the Llanvirn can be examined in clear section it is unfortunate that the original relationship has been destroyed by faulting.

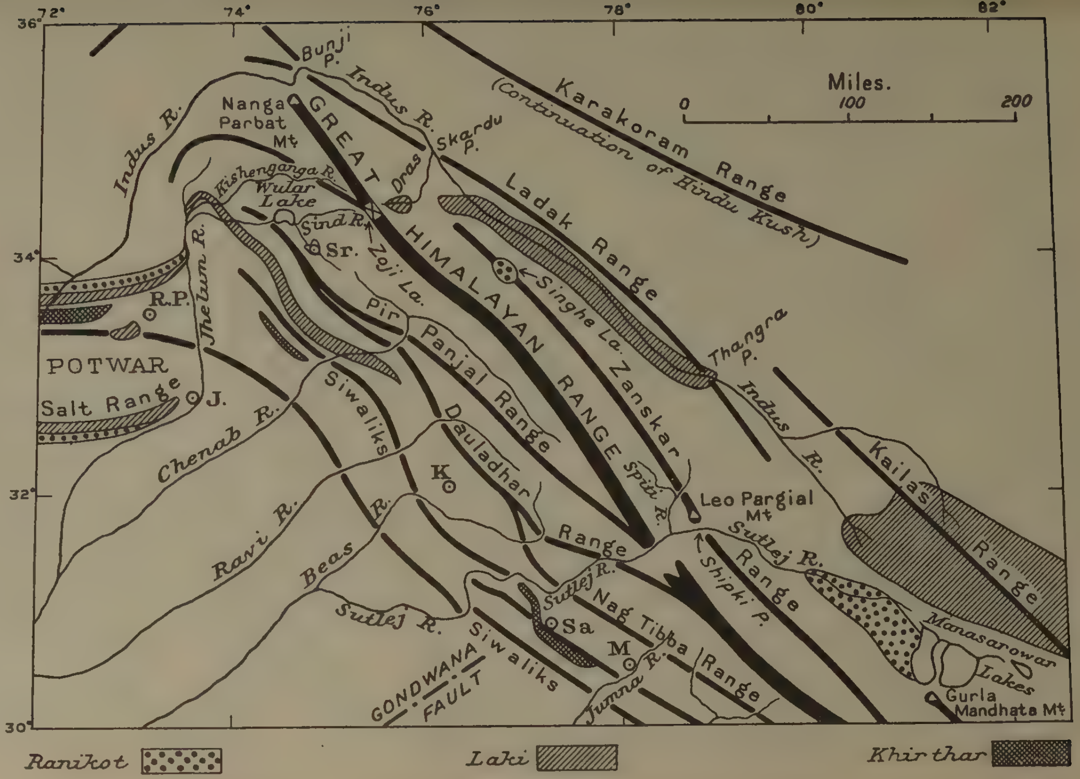
Note on Three Himalayan Rivers

By L. M. Davies

IN a recent paper (1940) I discussed the origins of the Indus, Jhelum, and Sutlej rivers. I suggested that the upper Jhelum resulted from the final severing of marine communications with Tibet by the rise of the north-west Himalayan axis at the close of Laki (Lower Eocene) times. The upper Indus probably originated rather later, from the overflow of Tibetan drainage ponded by the rise of this axis. The upper Sutlej I held to be much younger, and due to a geologically recent collapse of the main Himalayan axis along the line of an old (Gondwana) fault-trough. The following additional note is now offered in these connections:

It is a remarkable fact that the main Himalayan axis ends abruptly, in the north-west, with the great peak of Nanga Parbat. It is round this peak that the upper Indus circles, on its way from the Ladak Eocene deposits to the Potwar ones. That suggests that it was here—the vicinity of Nanga Parbat—that the advancing Himalayan system was checked sufficiently for the ponded trans-Himalayan drainage to escape; and the great depth to which the upper Indus has cut its bed (far lower than the upper Sutlej or the upper Brahmaputra have cut their beds) indicates that the upper Indus is the oldest of these three rivers which radiate outwards from the Manasarowar lakes. The significance of the fact that the upper Indus joins the Ladak Eocene deposits where the latter turn westwards to Dras, and carves its way backwards through those deposits to the Manasarowar lakes, repeatedly traversing the Ladak range in order first to join and then to keep that line, was noted in my paper.

It also seems significant that it is along the alignment of the Ladak Eocene deposits *after* they turn westwards to Dras that we find the upper Dras river flowing east, and the upper Jhelum waters (Sind and Kishenganga rivers) flowing west, on either side of the main Himalayan axis. These seem to be residual from the old connection between the Ladak marine deposits and the Potwar ones. The splaying out of Laki beds on the Potwar side of the Himalayan axis seems to witness to the disturbance which finally broke this connection; and a further relic of that connection seems to be the " wind gap " of the Zoji La, a flat-bottomed channel 500 yards broad and two miles long across the crest of the main Himalayan axis between



Text-fig. 1.—Rivers and Ranges of the N.-W. Himalayan Region.

the Dras and Sind rivers, which probably represents a former river bed connecting their drainage areas.

Of the three rivers radiating outwards from the Manasarowar lakes, the upper Sutlej seems to be much the youngest. Its extreme youth is indicated by the fact that it flows through breaks in the axes of the Siwalik foothills, and so must be younger than those foothills. The colossal nature of the event which gave it origin is indicated by the break in the main Himalayan axis—the connections of which on either side of the Sutlej are by no means clear—by the deep Shipki gorge opposite Leo Pargial on the Zanskar range, and by the disappearance of a great section of the Ladak range west of Gurla Mandhata. Thus the upper Sutlej would seem to owe its origin to a geologically very recent fracture of the Himalayan axis (accompanied by the rise of the Pir Panjal range ?) along the approximate line of the fault-trough mentioned in my paper. That structural weakness still exists along this line was suggested by the Kangra earthquake of 1905 ; for the latter had two foci, one at Kangra and the other at Mussoorie, on either side of the upper Sutlej (Middlemiss, 1910).

The attached figure may illustrate these remarks. Its representation of Himalayan ranges is after Burrard and Hayden (1907). Towns are indicated by letters as follows : *J.* Jhelum ; *K.* Kangra ; *M.* Mussoorie ; *R.P.* Rawalpindi ; *Sa.* Simla ; *Sr.* Srinagar.

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CORRESPONDENCE

THE OIL-FIELD BELT OF SOUTH-WEST IRAN AND IRAQ

Sir,—Those who have worked in South-West Persia for the Anglo-Iranian Oil Company will have read with great interest the account by Dr. G. M. Lees and F. D. S. Richardson of the latest geological advances that have been made there. "Unconformity," as playing any considerable part in the variations of thickness of the Lower Fars, seems to have finally gone by the board, yet in the period 1915–1920, it was only with the greatest difficulty that field workers obtained from the authorities at home a grudging admission that large thrusts and great flow sheets existed at all.

Most of the movement has occured from north-east to south-west, namely away from the main Zagros ranges, but a few back thrusts of considerable extent are found, notably at Lali, which district was first explored and mapped in 1917 by the writer and W. R. A. Weatherhead. A well was at that date recommended not far from the line of strike of the gas escapes shown in the section (p. 245), and well back from the Lali back-thrust, which would probably have got the Asmari limestone, but this was across the River Karun (shown as a nick in the section), and it is this formidable barrier which has, as much as geological considerations, prevented the Company from drilling further to the north-east. It is possible that the limestone dips much less steeply to the north-east than is shown.

The authors believe that the movement of the Lower Fars and the rocks above it in the Jehangiri syncline was from south-west to north-east (p. 248), but it would have been better to have extended the section to show the interpretation of their theory as far as the main Zagros Ranges, which rise to over 5,000 feet only 10 miles or so to the north-east. It seems to the writer more likely that the movement was in the opposite direction, and that the wave-like rise and advance of these folds was the propelling force. (The frontispiece of my book on *Earth Flexures* is an illustration of the Asmari fold adjacent to the area in question.) It is difficult to reconcile the supposed north-easterly movement of the Jehangiri with that proved to be south-westerly of the Lower Fars at Masjid-i-Suleiman only 20 miles away along the strike. There is no evidence of such a pivotal movement. As I conceive it, the evidence points to the probability that the Jehangiri syncline has moved forward to the south-west for 6 or 7 miles, shearing off the Lower Fars from the top of the Asmari anticline, and slumping the material into the depression under Zeloi, to the south-west of which there is again a deep syncline. The steep and rigid south-west flank of the Jehangiri syncline formed a propelling wall. By this interpretation the north-easterly sheet above the Lali thrust plane (not shown in the section) becomes a shallow "slop-over" underthrust by the adjacent great syncline to the north-east.

As for the mechanics that produced these and similar movements throughout the region, we suggest that the Zagros Ranges have in the past advanced (and are even still advancing), in wave-like undulations, and that the Lower Fars rock sheets ride in front of them, over Asmari anticline and Bakhtiari syncline, like surf-boards in front of a nearly breaking sea. The advancing "surf-board" scarps of the Lower Fars can be observed to-day, and profoundly modify the drainage lines.

There is probably no district in the world where the geology is better exposed, and where at the same time geological and geophysical talent has been more lavishly expended. But, as in all the sciences, the greater the knowledge attained the less we seem to know.

H. G. BUSK.

SANTA ELENA,
ECUADOR.

REVIEWS

THE PRINCIPLES OF ECONOMIC GEOLOGY. By W. H. EMMONS. Second edition. pp. xix + 529, with 329 Text-figs. New York and London, McGraw-Hill Co., 1940.

In the twenty-two years since the appearance of the first edition economic geology has made great progress, and the author has kept up so well with this progress that the second edition is practically a new book. The text has been completely re-set and re-written and the number of figures is increased by over 50 per cent. It may perhaps be well to point out for the benefit of readers not acquainted with the book that coal and oil are not included, in order to keep the volume down to manageable size. A check-over of localities known to the reviewer has only revealed one minor point for criticism: the Cleveland iron ores are not worked open-cast like those of the Midlands, as implied on p. 273, where also it is not made clear that the Cleveland, Frodingham and Northampton ore beds are all on different geological horizons. The section on the origin of sedimentary iron ores is rather inadequate, since no mention is made of the oolitic iron ores of England and Lorraine (chamosite ores of primary origin), which are certainly not due to replacement of calcium carbonate, whatever may be the case with the Clinton haematites, as described on p. 237. The very clear accounts of American mining regions will be welcome to English readers, who often have difficulty in finding the needle in the hay of the enormous literature.

R. H. R.

GEOLOGY FOR SOUTH AFRICAN STUDENTS. By G. N. G. HAMILTON and H. B. S. COOKE. pp. 240, with x plates, 61 text-figures, and a folding map. Johannesburg: Central News Agency, 1939.

For many reasons students beginning geology in, for example, the southern hemisphere must find the use of the ordinary British or American textbooks difficult. There are not only differences of scale and environment in physical geology, partly due to climate, but also the whole widely varying stratigraphical succession in different parts of the world. South African students, who wish to learn real geology as opposed to the cramming of textbooks, must be greatly puzzled by the enormous importance attached in Europe and America to the Lower Palaeozoic systems, which they simply have not got in Africa. On the other hand the treatment of the Precambrian in English books must strike them as inadequate. In Africa it is hard to see any reason for the arbitrary division into Palaeozoic, Mesozoic, and Tertiary. (Incidentally it may be remarked that this difficulty is by no means confined to Africa.) Hence an attempt to provide students with an elementary book suited to their own local geology is to be highly commended. In a way the book under review is not entirely new; it is founded on an earlier work published ten years ago, which has gone through three editions. But in its present form it is expanded, modernized, and entirely re-written.

Owing to its small size the book is necessarily much condensed, but it appears to include nearly all if not all the parts of the subject necessary for beginners. Owing to local circumstances the outlook is largely petrological and mineralogical, with a treatment of crystallography rather fuller than is usual. The chapter on Physical Geology is very short, and might well be expanded a little in future editions. Rather surprisingly the treatment of the arid or continental facies of denudation and deposition is very scanty.

As is well known, South African stratigraphy is difficult, owing to the immense variety of the older formations in often widely separated areas and the general absence of fossils. The authors have been very successful in giving an easily intelligible account of the present state of knowledge, and the maps showing in plain black the surface outcrop of each system are most useful. Especially notable is the close resemblance in the distribution of the only two marine fossiliferous formations, the Cape System and the Cretaceous, showing how nearly the continental block reverted to its previous condition after the strange episode of the Karroo system. The Cape system with its rich Bokkeveld Devonian fauna can only be regarded, to judge from its present distribution, as a coastal fringe, as the Cretaceous is admitted to have been. The Cape system represents the filling of the geosyncline in which the Fold Ranges were soon to develop.

It may then be justly said that the authors have been very successful in constructing a foundation on which students will be able to build up a detailed knowledge of the geology of their own country, with easy application when necessary to other lands with different geological environments and histories.

R. H. R.

GEOLOGICAL MAGAZINE

VOL. LXXVII. No. 6. NOVEMBER–DECEMBER, 1940

EDITORIAL

THE present double number for November–December completes the volume for 1940. The Editors feel satisfaction that in spite of inevitable difficulties it has been possible to carry on and to produce the successive numbers with very little delay. There has been no lack of contributions and at the present moment a considerable number of MSS. await publication. A greater difficulty is the supply of paper, which will only allow of a strictly limited number of pages per volume.

The Editors and Publishers hoped at the beginning of the year that it would be possible to make a reduction in the subscription rate in 1941. To our great regret, the loss of subscriptions from European countries has made this a vain hope, for figures supplied by the Publishers prove that any reduction in the present rate would now result in a loss. We are sure that Subscribers will recognize that these are " circumstances over which we have no control " and will continue their support of the Magazine. New subscriptions will materially assist in the realization of the hope for price reduction.

The Editors also regret that it will not be possible to proceed far with the projected series of articles on the Geology of British Oil-fields. Recent conditions in the Near and Far East have caused several companies to withdraw their sanction for publication. We are grateful to those companies which have given us permission to publish and to all the authors who have prepared MSS. for us, and hope to continue and complete the series after the war.

The Fossil Antelopes of Palestine in Natufian (Mesolithic) Times, with Descriptions of New Species

By Dorothea M. A. Bate

Introduction

A STUDY of the fossil vertebrate fauna of the Wady el-Mughara caves was published in 1937 (Bate, 1937), but at that time it had not been found possible to carry out an intensive examination of the antelope remains, except for the purpose of making the first record of a fossil hartebeest in Palestine. This omission was due partly to lack of sufficient time and partly to the fact that the specimens were generally in a very fragmentary state of preservation. Nevertheless, since remains of gazelles, together with those of *Dama mesopotamica*, occurred throughout the cave levels and were more plentiful than those of other species it was found practical to make use of these two types as climatic indicators, while other species were used as a control (Bate, 1937, fig. 1).

Recently Professor D. A. E. Garrod has kindly agreed to a study being made of the antelope remains from Kebarah Cave, the excavation of which still awaits completion. This cave is situated at about the same height above sea level, and only some ten miles south of the Wady el-Mughara caves. During the third season's work at the latter caves, in 1931, the preliminary excavation of Kebarah was undertaken by Mr. Turville Petre and Mrs. Baynes, who were then attached to the Joint Expedition of the American School of Prehistoric Research and the British School of Archaeology in Jerusalem under Professor Garrod's leadership (Turville Petre, 1933).

This work in Kebarah yielded a considerable quantity of animal remains, including two skulls of gazelles which, although lacking the dentition, are far more complete than any hitherto discovered. A study of these and other specimens, together with a re-examination of much of the antelope material from the Wady el-Mughara caves, has revealed several unexpected facts of great interest and importance in advancing our knowledge regarding the sequence of the faunal assemblages of the Pleistocene of Palestine.

For the sake of clarity some of these new facts are tabulated below :—

(*a*) It is now found that only extinct species of gazelles occur throughout the cave levels, from the Upper Acheulean (Tabun E) to the Mesolithic (Levels B of M. Wad, Shukba, and Kebarah).

Former records of Recent species of gazelles from other cave deposits in Palestine are doubtless due to erroneous identifications caused by lack of sufficiently complete specimens.

(*b*) Remains of about half a dozen species of gazelles have been recognized, though not yet described, from the earlier cave levels (Tabun E to Tabun B), that is to say up to the great faunal change which took place between Lower and Upper Levalloiso-Mousterian times. None of these are known to occur after this faunal break.

(*c*) Extinct species of gazelles, and also another antelope, from the later cave levels are found to be distinct, and these are unrelated to any Recent Asiatic forms. At least one, and possibly several, of these species appear to be related to the rather isolated Recent East African Gazelles, the *Gazella granti* group.

(*d*) The last-mentioned discoveries confirm what has already been suggested (Bate, 1933 and 1937, p. 153), namely that the Natufian (Mesolithic) mammalian faunal assemblage of Palestine is strikingly distinct from the fauna found living in the country at the present day. It is believed that this faunal change was accompanied by some climatic change.

DESCRIPTION OF NEW SPECIES

Genus *GAZELLA* Blainville

1816. *Gazella*, Blainville, *Bull. Soc. Philom. Paris*, p. 75. Pilgrim, 1939, p. 32.

Gazella decora [1] sp. nov. (Text-figs. 1, 3, 5*a*)

Diagnosis.—A Gazelle with skull somewhat larger than that of the Recent *G. gazella* of Palestine, but with horns actually and proportionately much larger. Braincase long, and comparatively narrow; supraoccipital and occipital condyles projected backwards. Basioccipital of medium width, basilar tubercles expanded and strongly developed. Sphenoid only slightly above the plane of the basioccipital, presphenoid wide and substantial. Face only moderately bent down on the basicranial axis as in *G. granti*. Interorbital area actually and comparatively stouter than in *G. granti*. Horn cores large, rising almost vertically directly above the orbits, then gently curving upwards and backwards. Horn cores arise close together, diverging gradually, but not widely separated at tips; size decreases gradually towards tips. Anterior and posterior surfaces of horn cores scored along nearly their whole length by furrows which may be of considerable depth. Horn cores nearly elliptical in transverse section. Supraorbital pits deep and centrally placed.

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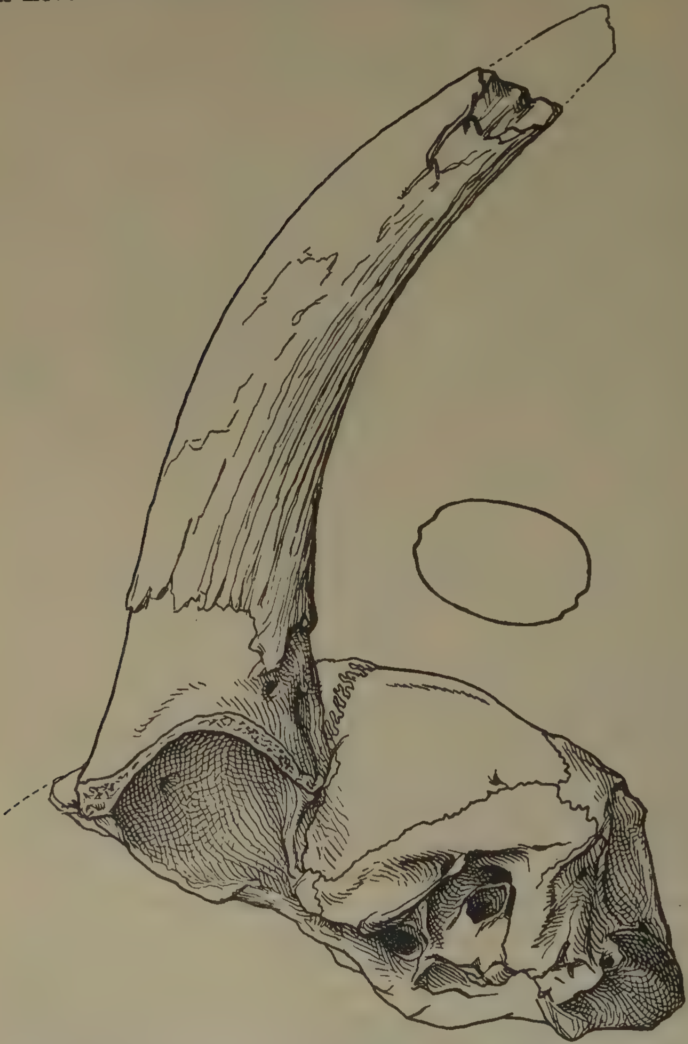
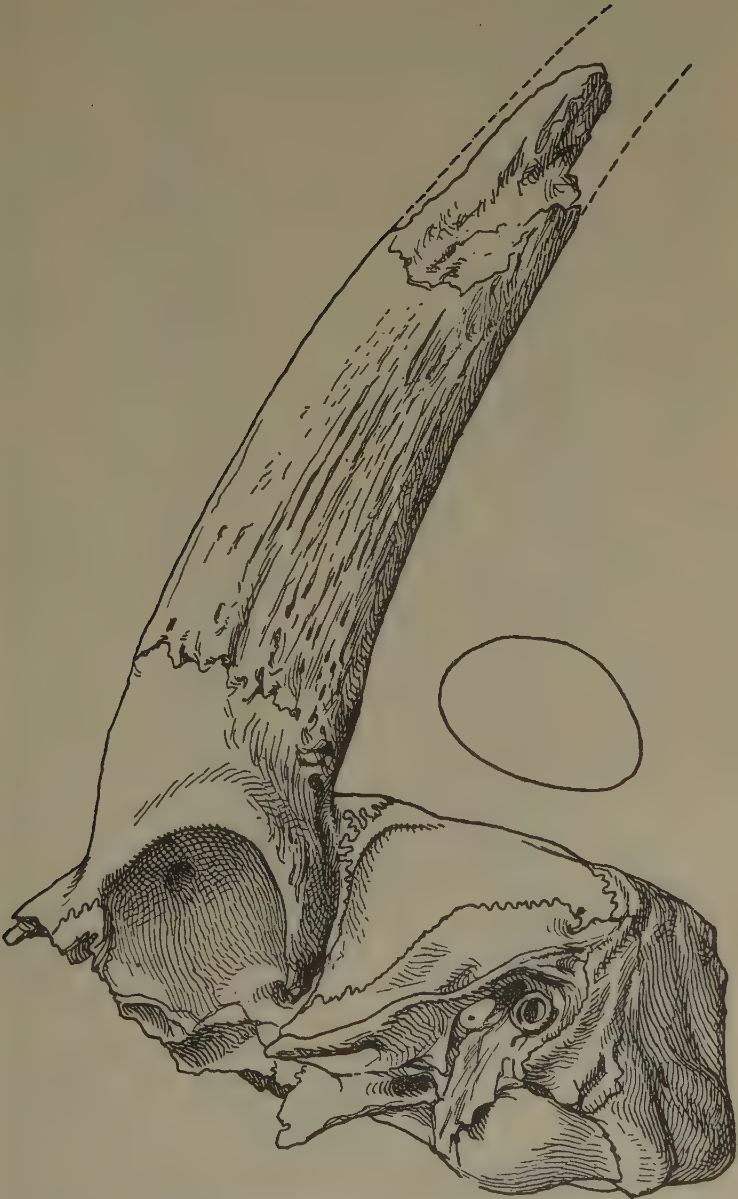
[1] See Isaiah xxxv, 2, " decor Carmeli " in Vulgate.

Holotype.—An incomplete skull of a male, with horn cores; from Level B of Kebarah Cave (Text-figs. 1, 3, 5*a*).



TEXT-FIG. 1.—*Gazella decora* sp. nov., lateral view of skull, holotype, with section of horn core, two-thirds natural size. From Kebarah, Level B.

Locality and Horizon.—Palestine, at present known from the Wady el-Mughara and Kebarah caves, also from Shukba cave in the Judaean hills. Obtained from Levels B 1 and B 2 of



TEXT-FIG. 2.—*G. granti petersi* lateral view of skull (Recent) with section of horn core, two-thirds natural size.

M. Wad, Level B of Shukba and from Levels B and C of M. Kebarah. Professor Garrod tells me that Level C of M. Kebarah is not represented in M. Wad, and that it is slightly older than Level B 2 of that cave.

Associated with both Upper and Lower Natufian (Mesolithic) industries, and also with the slightly older Kebaran industry (Kebarah C). *G. decora* is the dominant species of the Natufian Levels of the Wady el-Mughara caves and so far is not known from any level earlier than the Kebaran (Mesolithic), which seems to hint at its comparatively late arrival in the country.

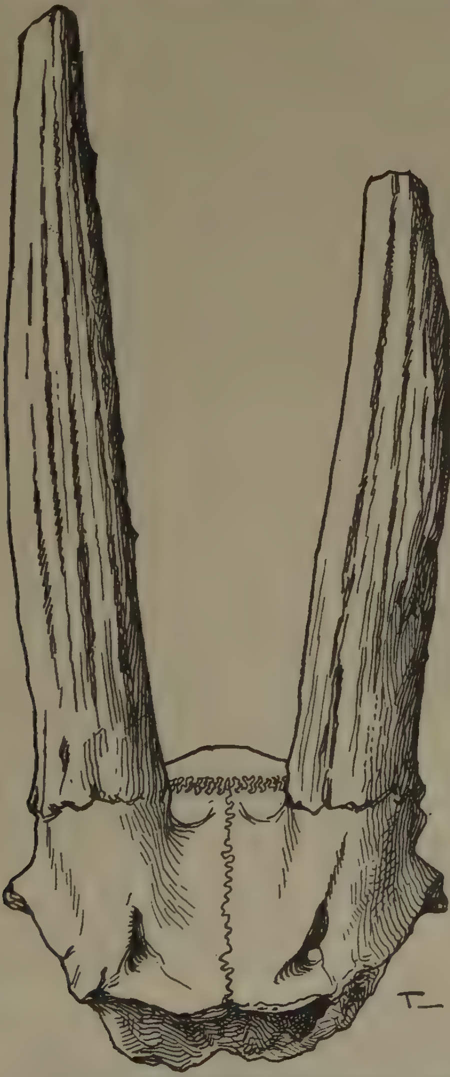
Description and relationships.—The general appearance of the skull of *G. decora* may be appreciated from the profile view of the holotype shown in Text-fig. 1. It is quite unlike that of any of the Recent Gazelles of Palestine, such as *G. gazella* (= *G. merrilli* Thomas), *G. dorcas*, or *G. subgutturosa*; nor indeed does it resemble that of any Recent Asiatic form.

The only Recent gazelles to which *G. decora* shows any close likeness are those forming the *G. granti* group which is now only found in East Africa. About eight races have been described and these include some of the handsomest of living gazelles, among which the horns reach the maximum size. All are large forms, considerably larger than *G. decora*; the skulls exhibit a number of structural affinities although the horn cores are not very similar. For the present it seems legitimate to suggest that *G. decora* should be included in the same group as *G. granti*, although it is wise to bear in mind that the chief characters in which they resemble each other are primitive ones. Briefly, these are the large size of the horns compared with that of the skull, the upright position of the horns which arise almost vertically above the orbits and the long brain case. Further, the position of the sphenoid and presphenoid in relation to the basioccipital is somewhat similar, but in the fossil species these bones are practically on a single plane, a primitive condition, while in the Recent *G. granti* the presphenoid is at a rather higher level, although not approaching the condition found in typical *Gazella*.

In the British Museum collection there is a skull of a Recent *G. g. petersi*, said to be the smallest of the group, from Jubaland (♂, 23.10.20.4) which is broken in an almost identical manner as the holotype of *G. decora*. This specimen is shown in Text-fig. 2, and a very careful comparison of these two skulls suggests that the face of the fossil species must have been bent at nearly the same angle on the basicranial axis as in the *G. granti* group, which is very different from that in typical Recent gazelles.

This had already been indicated by the position of the sphenoidal region in relation to the basioccipital referred to above.

The horn cores of *G. decora* arise close together and in the holotype these are only 22·8 mm. apart at the base of the roughened surface. They have an antero-posterior diameter of 32 mm., at the base, and a thickness from side to side of 25·5 mm.



Text-fig. 3.—*G. decora* sp. nov., anterior view of horn cores and frontlet, holotype two-thirds natural size.

That this does not represent the maximum size attained is shown by several isolated specimens in the collection; perhaps the largest is an example of the right side from Level B of M. Wad, which, at its base, has an antero-posterior diameter of 43 mm. and a transverse diameter of 29·4 mm. In a specimen of the Recent *G. granti* (Brit. Mus., 91.1.6.2) the corresponding measurements are 49·5 mm. and 34 mm. respectively.

A constant distinction is that in the fossil species there are deep groovings along the length of the anterior surface of the horn cores (Text-fig. 3). These groovings are absent in the Recent *G. granti* group and in practically all Recent species of *Gazella*. Similar grooves are present on the posterior surface of the horn cores of *G. decora*, *G. granti*, and many other species. Deep groovings on the anterior surface of the horn cores are not infrequently seen in fossil species such as *G. kueitensis*, referred to below, and in several forms of the somewhat later *G. sinensis* of China (Teilhard and Trassaert, 1938, text-figs. 21, 23–7).

The maximum width across the parietals in the holotype skull of *G. decora* is 60 mm., which is comparatively narrow, since the holotype skull of the decidedly smaller *G. esdraelonia* has a similar measurement. In *G. decora* the backward projection of the supraoccipital and the dorsal expansion of the occipital condyles are similar to the conditions found in *G. granti*, and are probably in great part due to the carriage of the head which is influenced by the large size and weight, as well as by the upright position of the horns. In the fossil species the basioccipital is comparatively narrower than in *G. granti*, and the basilar tubercles are much more strongly developed.

One of the several noteworthy characters in the skull of *G. decora*, already alluded to, which differentiates it from that of typical Recent gazellines is the great width of the presphenoid (Text-fig. 5*a*), in the holotype of *G. decora* it has a width of 9·5 mm. between the foramina rotunda, and this width is maintained throughout its extension forwards. In a skull of *G. g. petersi*, a considerably larger animal, this measurement between the above-mentioned foramina is 10 mm., while anteriorly the bone immediately decreases in width, thus approximating a more specialized condition.

The bullae are not preserved in the skull of *G. decora*, but what remains of the auditory meatus shows it to have been comparatively small, as in *G. granti*. The foramina rotunda are narrow, much longer than wide.

A portion of the back of a skull from Level B 2 of M. Wad resembles the corresponding part of the holotype skull of

G. decora and is referred to this species. Apart from this, other identified specimens consist of horn cores, for, in view of the presence of more than one species of fairly similar size in the same levels, it has so far been impossible to assign any of the isolated limb bones or dentition to one or other form.

Turning to the fossil record an extended search for species which might show a close connection with *G. decora* has been singularly unfruitful. It seems, however, likely that ancestral forms will be found in China. A suggestion of this is supplied by *G. kueitensis* from North China (Bohlin, 1938). This smaller and geologically older (? Middle Pliocene, Bohlin, 1938, p. 49) species seems to resemble *G. decora* in a number of characters, among which may be mentioned the upright position of the horn cores immediately above the orbit, the great length of the skull behind the horn cores, the backwardly projecting supraoccipital, the substantial width of the presphenoid, and the deep groovings on the anterior surface of the horn cores. All these points, with perhaps the exception of the last, are apparent in the figures of plate 1 of Dr. Birger Bohlin's work. With regard to the horn cores this author mentions (op. cit., p. 9) that the groovings vary in depth, but apparently the deepest of these markings are typically on the anterior surface.

Should *G. decora* and the *G. granti* group be proved to have had a common ancestor in Asia it seems likely that the latter reached their present habitat by a more southerly route than that taken by the Palestine species. So far no specimens of *G. decora* or *G. esdraelonia* have been discovered in cave levels earlier than those containing a Mesolithic industry, and this seems to suggest that these Gazelles were comparatively recent immigrants to Palestine.

None of the North African fossil gazelles figured by P. Thomas (*G. atlantica* Thomas, 1884, pl. 8, fig. 9) or by Pomel (1895), suggest any close relationship to *G. decora*. *G. granti*, it is true, has been recorded from a Neolithic deposit in Algeria (Joleaud, 1917 (1918), p. 218). Such an occurrence would not be surprising, but since it is based only on dental remains, it seems to require confirmation.

Gazella esdraelonia sp. nov. (Text-figs. 4, 5*b*)

Diagnosis.—A gazelle smaller than *G. decora*, about the size of the Recent *G. gazella*. Brain case long, comparatively wider than in *G. decora*, dorsal border almost horizontal, supraoccipital only slightly projected backwards. Basioccipital comparatively wider than in *G. decora*. Basilar tubercles strongly developed, sphenoid and presphenoid wide and stout, and only rising slightly above the horizontal plane of the basioccipital. Tympanic bulla comparatively short antero-posteriorly, well inflated, not narrowed anteriorly. Auditory meatus comparatively small, as in the Recent *G. gazella* and *G. granti*. Interorbital area comparatively wider than in *G. granti*.

Horn cores of medium size, rising almost vertically directly above the orbits, more vertical in position than those of *G. decora*. Basal portion of horn cores rounded internally and flattened postero-externally. Supraorbital pits large and deep. Orbit large.

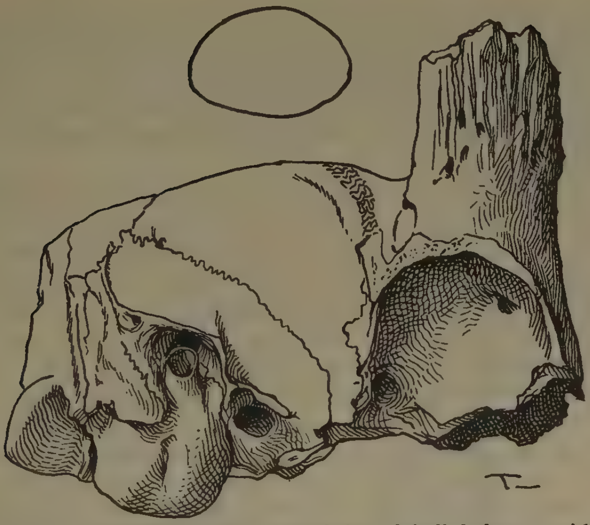
Holotype.—An incomplete skull, with the basal portions of the horn cores; from Level C of Kebarah Cave (Text-figs. 4, 5*b*).

Locality and Horizon.—Palestine: holotype associated with a Kebaran industry which is said to be Mesolithic, but earlier than the Lower Natufian of M. Wad. Horn cores tentatively ascribed to this species were found in Levels B of M. Kebarah, M. Wad, and Shukba (Natufian).

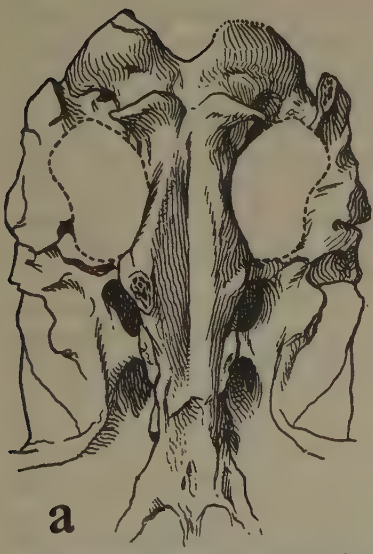
Description and Relationships.—It is believed that this gazelle should be included in the same group as *G. decora*, for the two holotype skulls present a number of resemblances as well as differences. It seems that the skull of *G. esdraelonia* shows perhaps even greater divergence from that of typical Recent gazelles than does that of *G. decora*. The horn cores of *G. esdraelonia* are considerably smaller, compared with the size of the skull, than those of *G. decora*, and probably it is owing to this that the supraoccipital and occipital condyles project only slightly backwards behind the nuchal crest. The horn cores in the holotype skull of *G. esdraelonia* are actually further apart at their bases than are those of *G. decora*; a measurement taken between the basal edges of the roughened surfaces is 27 mm. in the former, and only 22·8 mm. in the latter.

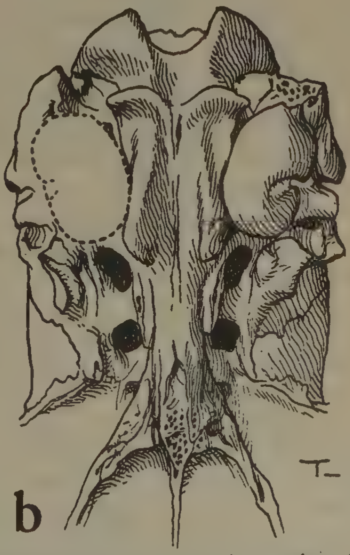
The short portion of the right horn core preserved in the holotype of *G. esdraelonia* has an antero-posterior diameter of 32·8 mm., and a transverse diameter of 22·3 mm. There are no indications of deep groovings, but not much insistence can be placed on this for deep groovings commonly originate at a higher level.

The supraorbital pits are comparatively larger and more inwardly placed than in *G. decora*. In *G. esdraelonia* both the foramen ovale and the foramen rotundum are wider compared with their length, and the foramen rotundum and the optic foramen are actually, as well as comparatively, larger than the corresponding foramina in *G. decora*.



Text-fig. 4.—*G. esdraelonia* sp. nov., lateral view of skull, holotype, with section of horn core, two-thirds natural size. From Kebarah, Level C.





Text-fig. 5*a*.—*G. decora* sp. nov. holotype, ventral view of posterior portion of skull.

Text-fig. 5*b*.—*G. esdraelonia* sp. nov. holotype, ventral view of posterior portion of skull. Both figures two-thirds natural size.

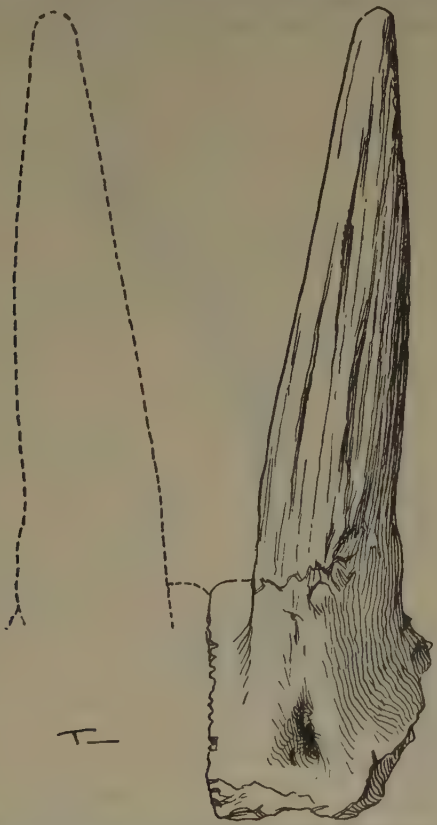
In view of the fact that *G. esdraelonia* and *G. decora* appear to be fairly closely related and that their remains were associated in the same cave levels, the possibility of the holotype skull of the former being that of a female of *G. decora* has been very carefully considered. The data available seem to weigh against this theory, however.

Perhaps the most important evidence in favour of *G. esdraelonia* as a valid species is the large size and the upright direction of the horn cores. In all gazelles in which the females are known to carry horns these are invariably much smaller than those of the male, and in *G. granti* they also differ in shape, position, and curvature. It will only be necessary here to compare the horn cores of *G. esdraelonia* with those of the female of *G. granti*. While the skull of the former is considerably smaller than that of the latter, a very different condition obtains in the case of the horn cores; in the Palestine specimen the antero-posterior diameter of the horn core is 32·8 mm., with a lateral thickness of 22·3 mm. In a Recent female example of *G. granti* the corresponding measurements are 22 mm. and 15 mm., while a second specimen proved to be only slightly larger.

It will be remembered that the large horn cores of *G. esdraelonia* rise more vertically above the orbit than do those of *G. decora*; a very different condition is found in the female of *G. granti*. The horn core of the male *G. granti* is so large that its base envelopes the whole of the upper border of the orbit, whereas that of the female is so very much smaller that it seems to rise from about the centre of the upper portion of the orbit. A still more strongly marked feature is the different slope at which the horn core ascends, that of the male *G. granti* starting almost vertically, while that of the female slopes rapidly backwards from its inception. The horn core of the male describes a graceful curve; that of the female is straight.

A European fossil with which the holotype of *G. esdraelonia* should be compared is the skull from Perrier attributed to *G. borbonica* by Depèret (1883–4, pl. 8). Resemblances are seen in the long brain case which is not posteriorly deflected abruptly downwards as in typical Recent gazelles, and in the large horn core which rises steeply almost directly above the orbit. Unfortunately the base of the skull, if preserved, is not shown in the plate. Differences which are apparent are the smaller size of the Perrier skull, and the elliptical section of the horn core with its rather more posterior origin and slightly backward slope.

Pomel (1895, ii, pl. iii) figured a skull from the Neolithic of Algeria under the name of *Dorcas subgazella* which, owing to its long brain case, at first sight hinted a connection with *G. esdraelonia.* A closer inspection suggests that this is the only resemblance, for while the Algerian specimen is much the larger of the two its horn cores, with a transverse diameter of 16 mm. at the base (Pomel, op. cit., p. 12), are both actually and comparatively so much smaller that it is likely that it represents the female of perhaps an allied form.

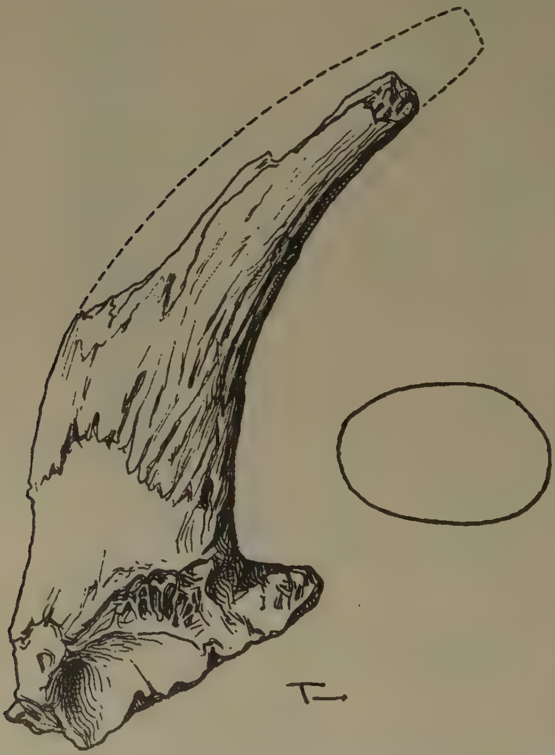


Text-fig. 6.—*G. arista* sp. nov., anterior view of left horn core and fragment of skull, holotype, with right horn core restored; two-thirds natural size. From M. Wad, Level E.

Gazella arista sp. nov. (Text-figs. 6, 7)

Diagnosis.—A gazelle of fairly large size, probably slightly larger than *G. decora.* Horn cores originating close together, and from immediately above the orbits; comparatively short, stout at base, distal half decreasing rapidly in size and bent sharply backwards. Transverse section of horn core elliptical; deep longitudinal grooving on posterior surface of horn core, furrows may also be present along the anterior border. Supraorbital pits deeply sunk.

Holotype.—A left horn core, complete except for the extreme tip, with a portion of the frontal, orbit and supraorbital pit present. From Level E of M. Wad (Middle Aurignacian) (Text-fig. 6).



Text-fig. 7.—*G. arista* sp. nov., lateral view of left horn core, paratype, with section; two-thirds natural size. From M. Wad, Level B.

Paratype.—An incomplete left horn core from Level B of M. Wad (Natufian) (Text-fig. 7).

Locality and Horizon.—Palestine; at present known from the Wady el-Mughara caves, Kebarah, and also from Shukba in the Judaean Hills. Obtained from Levels E (Middle Aurignacian), C (Upper Aurignacian), and B (Natufian) of M. Wad, and from the Natufian of M. Kebarah and Shukba.

Remarks.—As *G. decora* was the dominant species of gazelle in the Natufian Levels, so *G. arista* seems to have been dominant in the Middle Aurignacian. Thus thirty-five horn cores have been identified from Level E of M. Wad, one from Level C of the same cave, and eight only from the Natufian of M. Wad, M. Kebarah and Shukba together. The holotype (Text-fig. 6) is from the typical horizon and is one of the most complete specimens so far known, including part of the frontal suture and a portion of the orbit. This enables the position of the horn in relation to the skull to be ascertained, and this position is found to be much the same as in *G. decora.*

The holotype horn core has an antero-posterior measurement of 42 mm. at the base of the roughened surface, with a lateral diameter at this point of 25·5 mm. In the example from Level B of M. Wad (Text-fig. 7) these measurements are 42 mm. and 28 mm. respectively. In the text-figure this latter specimen has been restored in outline from the holotype.

Relationship.—Nothing very definite in regard to relationship can be ascertained from isolated horn cores, nevertheless some information is provided. Partly on account of the absence in the collection of any gazelline jaws and teeth of large size it seems legitimate to surmise that in *G. arista*, as in *G. decora*, the horns were larger, compared with the size of the skull, than is usual in typical modern gazelles. The horn cores of *G. arista* are very distinct in shape from those of *G. decora*, but their position relative to the skull appears to be similar, and this suggests that in *G. arista* we have a species belonging to the same assemblage as the extinct *G. decora*, *G. esdraelonia*, and the Recent *G. granti* group.

Turning to the fossil record it is found that the only species with which the horn cores of *G. arista* can be closely compared is one from the Pleistocene of Algeria described and figured by Pomel (1895) as *Antilope* (*Dorcas*) *crassicornis*. In Pomel's fig. 3 of pl. i, a horn core in profile view shows a close resemblance to that of *G. arista* in size, shape, curvature, and in its position in relation to the skull. The anterior view of the same specimen (fig. 2) determines that the Algerian is not identical with the Palestine species, but the suggestion that these are two allied forms receives further support from other examples on pl. xiii of the same work. The type specimens of *A. crassicornis* were obtained from the Pointe-Pescade cave (Pomel, 1895, p. 19) and other specimens are now known from a cave excavated by

Professor Arambourg (1931). Both these caves contained an early fauna, so it is possible that the North African species may be a somewhat earlier form than *G. arista.*

Two specimens of horn cores from Nihowan, North China, figured in pl. xi, figs. 3 and 4 (Teilhard and Piveteau, 1930) and attributed to *G. sinensis*, seem to be not unlike those of *G. arista*. Not much weight can, however, be placed on this for the moment, for if these two specimens are rightly identified more complete examples, such as the skull shown in fig. 2 of pl. xi referred to above, prove that *G. sinensis* is very distinct from *G. arista*. Furthermore, in the written description of *G. sinensis*, it is mentioned (op. cit., p. 65) that the horn cores are only slightly laterally compressed, the reverse being the case in those of *G. arista*.

I have not found any Recent species in the British Museum collection which carries horns resembling those of *G. arista*.

Genus *Kobus* A. Smith

1840. *Kobus* A. Smith, *Ill. Zool. South Africa* (*Mamm.*), pl. xxviii. London.

Kobus ? *cananites* sp. nov. (Text-figs. 8, 9)

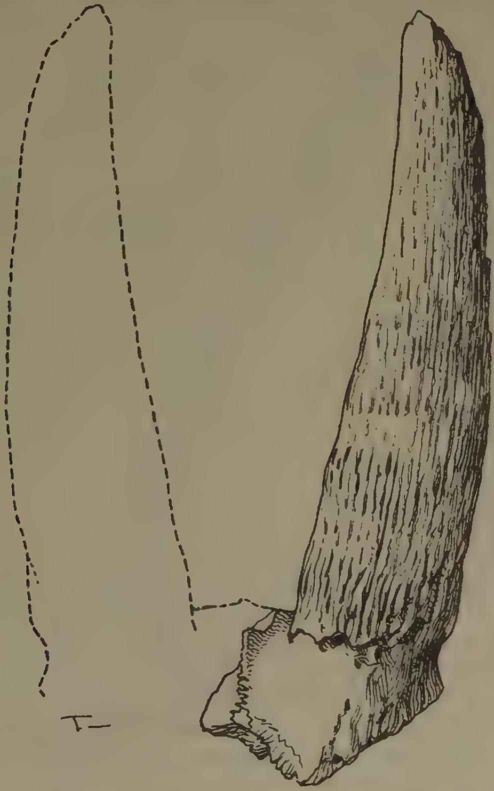
Diagnosis.—A (?) Reduncine of medium size. Frontal suture swollen. A shallow cavity present behind and at base of horn cores. Horn cores originate close together, almost circular in cross section. Entire surface of horn core rugose, unlike the fine texture generally seen in *Gazella* ; faint transverse undulations present on the inner surface of the horn core, due to pressure of the cross ribbings of the horny sheath.

Holotype.—A unique left horn core, complete except for the extreme tip, with a small portion of the frontal suture present. From Level B (Natufian) of M. Wad (Text-figs. 8, 9).

Locality and Horizon.—Palestine ; at present known from Level B (Natufian) of M. Wad.

Description and Comparisons.—The holotype horn core of *Kobus* ? *cananites* measured in a straight line from the frontal suture to the slightly abraded tip gives a length of 14 cm. It is nearly circular in cross section throughout its length ; about 23 mm. above the " burr " the antero-posterior diameter is 37 mm. and the lateral diameter 32 mm. This is a more rounded section than is typically found in the genus *Gazella*. The horn cores of *K.* ? *cananites* originate close together, about 20 mm. apart in the holotype. There is a deep groove in the posterior surface of the distal end of this horn core and the texture is similar in type, but rather closer and finer, than that seen in many of the Recent Reduncinae, such as *Kobus*.

The faint semi-annular markings on the inner surface of the horn core of *K.* ? *cananites* are an important character. Although the outer horn sheaths of gazelles are often strongly ridged I have never found a specimen in which this ridging is delineated on the horn cores. In many of the Reduncinae, however, such markings are often deeply impressed on the anterior and internal surfaces of the horn cores.



Text-fig. 8.—*Kobus* ? *cananites* sp. nov. Anterior view of left horn core and fragment of skull, holotype, with right horn core restored; two-thirds natural size. From M. Wad, Level B.

In his diagnosis of the subfamily Reduncinae Dr. Pilgrim (1939, p. 49) gives as one of the characters that the horns are " almost upright or moderately tilted backward, but invariably curving forward either from the base or only in their upper part. . . ."

The absence of any such recurvity in the Palestine horn core is one of the reasons which has caused me to refer it only provisionally to the genus *Kobus*. I have found a few species among the Recent Reduncinae in which this forward curvature of the horn cores is hardly noticeable, but a search through the collection of the Zoological Department of the British Museum (Natural History) has revealed no species with horn cores closely resembling that of *K.* ? *cananites*. It seems probable that the discovery of more complete specimens will show that the Palestine species should be included in a distinct genus.

In the holotype of *K.* ? *cananites* the presence of a cavity below the base of and behind the horn core is of considerable interest, since Dr. Pilgrim tells me that a depression in this position is characteristic of the Gazellinae, and is very marked in the Reduncinae. In the Palestine fossil this cavity is shallow, and almost separated into two parts by a raised median area.

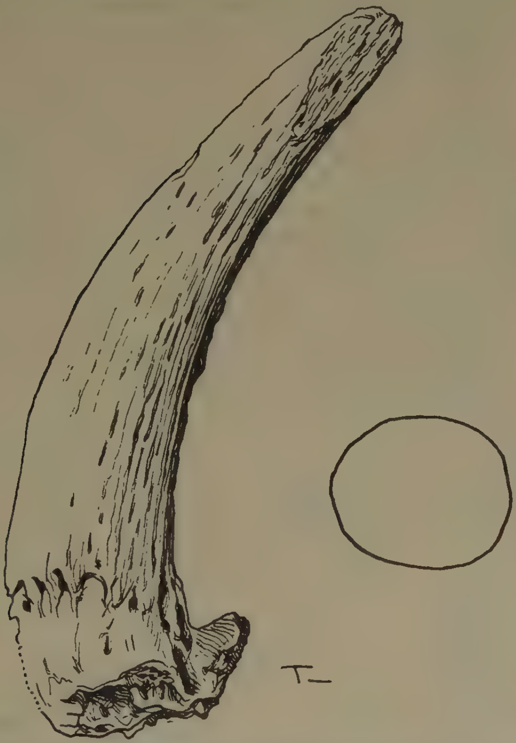
Khomenko (1913) described a genus, *Procobus*, with two species from Teraklia, and a number of genera of Reduncinae have been recorded from deposits in India (Pilgrim, 1939). Among the latter the frontlet described as " Reduncinae genus indet. (cf. *Indoredunca*) *theobaldi* (op. cit., p. 114, pl. iii, figs. 10, 10*a*), of which a cast is preserved in the British Museum (M. 15827) is suggestive of some affinity with the group to which *K.* ? *cananites* belongs.

It is of special interest to find that the species at present known to show the closest resemblance to *K.* ? *cananites* is a fossil one from Algeria. This is represented by an incomplete horn core from a bone breccia in that country described by Pomel (1895) under the name of *Antilope* (*Dorcas*) *nodicornis*. Figs. 1 and 2 of pl. v show a horn core very similar in appearance to the one from Palestine, except that the annulations are present on the external as well as on the internal surface. A further possible difference is suggested by the author's remark (p. 18) that the cross section is elliptical.

Fossils from Algeria so far directly ascribed to *Kobus* or closely related forms, such as the large *Antilope tournoueri* (P. Thomas, 1884, p. 15, pl. i, fig. 1) and Pomel's *Antilope* (*Oegoceros*) *selenocera* (1895, pl. vi, figs. 1–3) show no resemblance in their horn cores to the specimen from Palestine.

That a member of the Reduncinae, which includes the Water Bucks, should have lived in Palestine during Natufian times when climatic conditions were decidedly dry is not so anomalous as it might at first appear. This may be realized from a quotation from Roosevelt and Heller (1915, ii, p. 514), who wrote of

Kobus leucotis : "They were found on the immense dry flats, sometimes among the scattered thorn-trees, sometimes out on the stretches of short grass ; although in the neighbourhood of water, they sought it merely to drink . . . they were grazers like the rest of this genus." Further, it is worth remembering that closely related forms such as the Water Bucks (*Kobus*) the Reedbucks, and the Rock Reedbucks vary in habits from swamp and plains haunting to dwelling on rocky hillsides and steep mountain slopes.



Text-fig. 9.—*Kobus ? cananites* sp. nov., lateral view of left horn core, holotype, with section ; two-thirds natural size.

The Natufian Fauna and Climatic Conditions

The Mesolithic mammalian fauna of Shukba and M. Wad was associated with a human industry which displayed so many original features that Professor Garrod judged it necessary to distinguish it by a local name (1932, p. 8, and 1933, p. 261).

She divided it into Upper (B 1 of M. Wad) and Lower (B 2 of M. Wad) Natufian. The Kebaran (Kebarah C), slightly older than Level B 2 of M. Wad, is also considered to be Mesolithic by Professor Garrod. Neuville (1934) separated the Natufian into four stages, thus emphasizing the very considerable period of time which is embraced under this heading. So far it has not been possible to make any faunal distinctions between these different sections, though doubtless a progressive change will become apparent when more extensive collections enable a detailed survey to be made.

Soon after the discovery of the Natufian human remains, Sir Arthur Keith remarked that they " were a peculiar people not to be identified with any living race " (Keith, 1934, p. 46). A full description of the skeletons will soon be published by Mr. McCown. They are a race which had achieved the beginnings of art and agriculture (Garrod, 1937) and had domesticated a dog (Bate, 1937), p. 175. All this suggests that they had begun to interfere with the environments of the natural fauna.

The following is a list of the mammals known at present from Natufian layers :—

***Erinaceus carmelitus*
E. cf. *auritus*
†*Hyaena crocuta*
Canis familiaris cf. *matris optimae*
Vulpes vulpes
Meles meles
Martes cf. *martes*
Vormela peregusna
Ursus sp. (small)
Felis cf. *sylvestris*
Panthera pardus
Spalax sp.
Lepus sp.
Sciurus cf. *anomalus*
Microtus cf. *guentheri*
Gerbillinae
Sus scrofa (var.)
Capreolus capreolus
†*Cervus elaphus*
†*Dama mesopotamica*
Capra sp.
**Alcelaphus* sp.
†*Bos* sp.
**Gazella decora*
**G. esdraelonia*
**G. arista*
**Kobus ? cananites*
**Equus* cf. *caballus*
E. hermionus
Procavia cf. *syriaca*

Those species marked * are extinct, those marked † are no longer found in Palestine, but exist in other, though not contiguous, countries.

That the number of species of gazelles would be increased were more complete specimens available is suggested by the presence of a quantity of mandibular rami and a few limb bones which are considerably smaller than those of the Recent

G. subgutturosa, and are therefore too small to have belonged to the new species described in the earlier part of this paper.

The considerable number of extinct species included in this Mesolithic mammalian fauna both emphasizes its difference from the Recent fauna of the country, and is of peculiar interest inasmuch as it is most unusual to find so large a number in a deposit of this comparatively recent age.

It may be of interest in this connection to remember that in the Mesolithic of North-Western Europe only one or two extinct species occur, and that only in the earliest section of this period (Clark, 1936).

Species present which need open country and dry conditions are the antelopes, wild goat, large horse, half-ass, and the rodent mole (*Spalax*). This last was represented by a greater number of specimens in Level B of M. Wad than in any other Level of that cave. At the same time it is interesting to note that remains of Gerbils (desert-loving forms) were practically absent. Of all the animals enumerated in the above list remains of gazelles were by far the most plentiful, not only in M. Wad, but if anything even more so in the corresponding level of M. Kebarah. This numerical supremacy is clearly shown by the collection from the Natufian layers of M. Wad which yielded nearly two thousand specimens representing gazelles, while the greatest number of any other species was eighty-eight. The preponderance of gazelles over the typically woodland Fallow deer was greater during the Natufian than in any other section of the considerable period covered by the Wady el-Mughara excavations (Bate, 1937, fig. 1). This rich antelopine fauna of Natufian times suggests that a period of considerable dryness had set in.

It is of great interest to find that Dr. Avnimelech has reached somewhat similar conclusions based on a study of the Mollusca, from which he concludes (Avnimelech, 1937, p. 91) that the climate of the Upper Palaeolithic resembled that of the present-day both as regards temperature and humidity. He further suggests that the early part of the Mesolithic was characterized by a climate both warmer and drier than that of to-day, causing the whole of Palestine to exhibit semi-desert conditions such as are found in the districts of Gaza and Beersheba to-day.

This latter suggestion is not entirely supported by the Mammalia, for like all the known cave faunas of Palestine that of Natufian times was very mixed in character. Accompanying the types of dry and open country were the Red and Fallow Deer, both very rare and probably no longer found in the country after this period, a large Ox, and a very large Pig of modern type which seems to have been plentiful. Among the bird remains from Kebarah those of Anatines, including a small goose, were most numerous ; but these may represent migrants during the rainy season. Some of these forms certainly require woodland and scrub and a supply of water. These differing factors suggest considerable heat and an approach to desertic conditions in certain areas, tempered by woodland growth on hills and in ravines, together with a not inconsiderable supply of permanent water, perhaps a savannah type of environment. It may be remembered that the locality of the Wady el-Mughara, from which most of the faunal evidence is derived, is singularly well situated for access to country of varied types, mountains are near, rivers near their entry to the sea, whose undrained banks would provide swamps, and the extensive plains of Esdraelon and Jezreel, giving entry to the Plain of Beisan and the Jordan Valley.

FAUNAL AND CLIMATIC CHANGES

To a varying degree, all animals are in their morphology, anatomy, and physiology, adjusted to certain types of environment, in other words to the sum total of external factors acting in and upon the area inhabited. Most of these factors are climatic, and consequently it is reasonable to assume that a faunal change is connected with, if not caused by, a climatic change.

Owing to the fact that certain species are able to adapt themselves to various types of environment or climate and therefore may be tolerant of sometimes widely different conditions, especially regarding temperature, it is unwise to base the climatic interpretation of a fauna on isolated species. Wherever possible a faunal complex should be considered and the species scrutinized as to their value as climatic indicators.

From its inception the study of the Mesolithic fauna of Palestine (Bate, 1932 and 1933) showed that it included extinct species and others which are no longer found living in the country. Later investigations confirmed this difference (Bate, 1937, p. 153), which is even more strongly emphasized by the recent discoveries. The brief account of the Natufian mammals given in the preceding section will have clearly shown how different this assemblage was to that of Recent times. Were only a few forms implicated in this change it might be reasonable to suggest that weak species had been overcome and supplanted by more virile forms extending their area of distribution. It is quite otherwise, however, in the present case which has involved the replacement of a considerable portion of a fauna including elements with such different biological requirements as a hedgehog, a hyaena, and a group of gazelles, together with other antelopes. The described faunal change seems to demand the wider interpretation, though it is not claimed that this late faunal change was so complete as the one which took place between Lower and Upper Levalloisian times (Bate, 1937, p. 149), which has more the appearance of a break.

The composition of the Natufian mammalian fauna suggests that its disappearance and replacement must have been associated with an alteration of climatic conditions, which took the form of the oncoming of a more humid phase. Known facts do not seem to indicate any very appreciable difference of temperature.

As yet no direct geological evidence of the economy of this climatic change seems to have been discovered in Palestine. It must, however, be remembered that very little is known of the period which intervened between the end of the Natufian and Recent times.

The Natufian industry was succeeded by the Tahounian of which so far not a great deal is known, though it has gradually become evident that this culture persisted for a long time. Of the accompanying climatic conditions and fauna almost everything has still to be learnt. It is to be hoped that when Mr. Waechter is able to continue his excavations in Transjordan (Waechter, 1938), some light may be thrown on these important aspects of a little-known period.

When we turn to neighbouring countries it is found that many facts are known which demonstrate the occurrence of a post-Mesolithic period during which there was greater precipitation than there is at the present day in the regions concerned. Some of these will be briefly referred to since they doubtless have some bearing on the Palestine problem. Palestine could indeed have scarcely remained unaffected by a climatic phase which seems to have embraced an area so extensive as to include at least the whole of North Africa, including Egypt, and probably also Arabia.

It is already well known that the present-day climate of North Africa was immediately preceded by one characterized by a heavier rainfall and more widespread fertile conditions. Records dealing with various aspects of this are so numerous that a large literature has arisen on the subject which cannot be dealt with here. These records are of two kinds, supplied by the present and the past. The former consist of the survival of aquatic animals such as fish and crocodiles, still found living in small areas of water situated in isolated parts of the Sahara.

The evidence from the past is twofold, being provided by rock engravings and also by deposits of human industries together with animal remains. Examples of each of these have been known separately for a long time, but it remained for Professor Vaufrey to prove, through his own researches in North-West Africa (1939, chapter iii), that the naturalistic rock engravings of animals are contemporary with an industry which he labels as Neolithic of Capsian tradition. The fauna represented both in the rock pictures and in the deposits is one which could exist only in areas provided with a plentiful supply of permanent water, such as large rivers or lakes. It includes numerous fish, among them Siluroids, with river turtles (*Trionyx*), crocodile, hippopotamus, and the marsh haunting antelope, *Limnotragus*. Others, perhaps less dependent on the presence of abundant water, are wart hog, African elephant, rhinoceros, giraffe, antelopes, and bovids, and a rattel (*Mellivora*).

In Egypt Miss Caton-Thompson and Miss Elinor Gardner's researches have clearly demonstrated that, following on a dry climatic phase, there was a high level in the Birket Qarun in the Faiyum during Neolithic times (Caton-Thompson and Gardner, 1929).

Similarly a late damp climatic phase has been described from Uganda (Wayland and Burkitt, 1933), and from East Africa where Dr. Leakey correlates his Nakuran Wet Phase with that of the Faiyum Neolithic (Leakey, 1936, table facing p. 136).

Fossil Mammalian faunas are not yet known from Arabia, but, largely through Mr. Philby's explorations supplemented by Mr. Bates's valuable work on his collections (Bates, 1936, 1937), it is now well known that this country is rich in relic avifaunas, although unfortunately not much can be said as yet regarding their dating. Two of these faunas found in the west are of special interest for each seems to have survived from a time when more humid conditions prevailed. One is palaearctic and includes interesting woodland forms such as distinct species of woodpecker and magpie. This assemblage is generally restricted to high altitudes where fertile conditions prevail, the magpie for instance is found only in the Asir Mountains at heights of 7,500 feet and upwards.

The second assemblage is Ethiopian and is chiefly found in the southern Tihama, a tract of country in western Arabia lying between the coast and the great escarpment, and of which

Mr. Bates (1938, p. 441) wrote : "... its deep ravines containing streams and its terraced slopes planted with coffee, has already been spoken of as the home of many tropical African birds." The distribution area of some of these species has already reached considerable elevations, for instance, weaver birds are found up to a height of nearly 7,000 feet. Farther south in the Yaman and the Hadhramaut Ethiopian species such as hornbills, weaver birds, the paradise flycatcher, and others are found, though more sparsely and only in limited areas. This distribution suggests that the Ethiopian avifauna may be later than the Palaearctic, and that possibly it flourished at a fairly recent date.

The evidence given above of widespread humid conditions which prevailed in neighbouring countries during the Neolithic or even later may well cause us to look forward to the discovery of evidence of a similar occurrence having taken place in Palestine. As a result of the work of the Egyptian University Scientific Expedition to South-West Arabia, some relevant geological facts are already known. Dr. A. S. Huzayyin (1937, p. 513) recorded that, " During Quaternary times this corner of Arabia seems to have had two major Pluvials separated by an Interpluvial. . . . In recent times there was a new wet phase. . . . which we believe to have continued well into the Christian era. . . ."

FAUNAL COMPARISONS

Unfortunately Mesolithic faunas are not yet known from Transjordan, Irak, or Arabia. In these countries one might expect to find interesting parallels with the Palestine fauna of Natufian times, and indeed throughout the stages of the Pleistocene. Looking westwards it is becoming increasingly apparent that for comparisons with the faunas of Palestine during the latter part of the Pleistocene we must turn, not to the north of the Mediterranean where Dr. A. C. Blanc (1936) has shown that *cold* climatic phases occurred repeatedly, but rather to its southern borders, and perhaps to a lesser extent to the Islands.

From time to time throughout the Pleistocene there must have been the opportunity of an exchange of species between Palestine and North Africa.

Eventually a close connection will probably be found to exist between the Palestine Natufian fauna and that of the corresponding deposits of North Africa. As already noted earlier in this paper, there are resemblances between certain fossil antelopes of the two countries, such as *G. arista* with *G. crassicornis*, and

Kobus ? *cananites* with *G. nodicornis*, which is probably not a true gazelle. This last is said to have come from a deposit of Neolithic age.

Unfortunately there is considerable confusion both in the dating and the identifications of what is evidently a very rich and interesting fossil antelopine fauna in North Africa. Fresh and properly documented collections are urgently needed to supplement the earlier ones. In reviewing the Pliocene and Quaternary gazelles of Algeria, Joleaud (1918 (1917), p. 219) made the misleading assertion that *G. triqueticornis* is the only species of gazelle described by Pomel which cannot be referred to a form now living in North-West Africa.

G. triqueticornis is certainly an extinct species of antelope, but it is not a gazelle. It is equally evident from his figures that several of the other gazelles described by Pomel (1895) represent extinct forms, some of which are referred to above, and in the systematic section of this paper.

With greater discernment, Professor Arambourg wrote in 1934 (p. 47) that the Quaternary gazelles are amongst the least known fossils of " Berbérie ".

It is not only the fossil antelopes and other species which suggest a faunal comparison between Palestine and North Africa. The types of faunas and their succession during the Middle and latter part of the Pleistocene seem to have unfolded on parallel lines. Concerning Algeria, Professor Arambourg (1934, p. 34) writes that he found in the filling of the caves Mousterian industries associated with a fauna of primitive type, accompanied by indications of a damp tropical climate, very different from that of the present day. Upper Palaeolithic times are characterized by the disappearance of the hippopotamus and leptorhine rhinoceros fauna, indicating a change in climatic conditions with the approach of a period of desiccation, with a reduction of forest and pasture areas accompanied by the gradual disappearance of the large herbivora.

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The Geology of Basutoland

By G. M. Stockley

IT is now some thirty-two years since any observations on the Geology of Basutoland have been made. The Rev. S. S. Dornan of the French Protestant Mission may be considered to be the only serious contributor and he published three short articles on the geology during the period 1905–8. The writer was invited by the Colonial Office to carry out a reconnaissance geological survey of the territory, and the following notes may be considered a summary of his general observations.

Basutoland is situated within the Union of South Africa: it is bounded on the west by the Orange Free State and Natal, on the east by Natal and East Griqualand, and on the south by the Cape Province. It comprises an area of 11,716 square miles, two-thirds of which is occupied by a thick covering of Karroo basalt; the region of the basalts is mountainous country rising from a base level of about 6,000 feet to more than 10,000 feet above sea-level. Mont aux Sources, the highest mountain in Basutoland and in the Union of South Africa, has an altitude of 10,763 feet. The topography is governed by the drainage of the Caledon and Orange rivers, which flow to the south-west. To the east of the Caledon River (which forms the western territorial boundary) drainage there are the Malibamatso, Cinquyane, Semena, Khubedu, Upper Orange, Mokhotlong, and other rivers which converge on the main Orange River valley. Between these two main drainages there is the smaller intervening valley of the Kornet Spruit. The Drakensberg Mountains form a south-eastern, eastern, and north-eastern boundary range to the territory and their steep escarpments are an effective barrier to most forms of locomotion. It is the western drainage of this prominent mountain range, together with its western and south-western subsidiary mountain ranges, that constitute the upper portion of the drainage basin of the Orange River. Many of the intervening ranges attain altitudes of 10,000 feet and the subsidiary ridges not uncommonly reach to 8,500 and 9,000 feet.

To the west of this mountain region and in the immediate vicinity of the Orange River there lies a strip of lower lying country. From north to south elevated plateaus may be observed stretching across the western lowlands in a general equatorial direction. In some cases either Cave Sandstone or basalt, in others both Cave Sandstone and basalt form the floor of this peneplain. Excellent examples of these features are the Leribe, Berea, and Qeme plateaus, whose general level is about 5,800–6,200 feet. Fragments of this peneplain form a constant feature throughout Basutoland: almost every valley of the western streams exhibits small relics at about this altitude. As the traveller penetrates into the interior he cannot fail to be struck with the slight inclination of the sandstone-basalt junction, which causes the floor of this peneplain invariably to be basalt.

A second but much less defined peneplain occurs at about 7,500 feet. It can be recognized above the Lebihan Falls of the Maletsunyane River. This peneplain may be considered to be the cause of the falls. The Maletsunyane River had not sufficient volume and corrosive power to cut back an even grade from the earlier 7,500 ft. peneplain to that at 6,200 feet during the elevation of the country. This second peneplain may also be observed at Mokhotlong Camp (the administrative station of the north-eastern district), and truncated portions of it are frequently seen in the upper reaches of the main tributaries of the Orange River system.

A third peneplain has been identified by Dixey; he states:—

> ". . . the 8,500 to 9,500 feet even crest of the Drakensberg represents the end Jurassic peneplain, and the lower surface of 6,500 to 7,500 feet on the backs of the long south-easterly spurs, the mid-Tertiary peneplain."

(This statement was communicated privately to the writer by Dr. S. H. Haughton, to whom the writer is also indebted for introducing to him other important papers by South African geologists.)

The writer agrees with Dixey that there is a third peneplain exhibited on the spurs of the Drakensberg mountain ranges. It is well exemplified in Basutoland. Every mountain range descends by an even grade to about the 8,590 ft. level, below which there is a steep incline to the 7,500 ft. level, below which again there is a second steep incline to the 5,800–6,200 ft. level. It is probable that the uniform level of 10,000 feet and more, so characteristic of the highest mountain ranges, represents the original surface of the last volcanic outpouring.

In passing it is interesting to note that a relationship may be shown to exist between the distribution and the density of the native population and the physical geology. In the first case the upper junction of the Cave Sandstone denotes the boundary line between areas saturated with native inhabitants and those still under-saturated. An exception to this generalization is the upper Tsoelike valley of Qacha's Nek. But the figures from the last census of 1936 show that there have been certain increases of population for the various districts. For Berea district there is the exceptional case of a decrease in population. Now Berea district is occupied by a high proportion of the Stormberg sedimentary rocks and the district is so over-populated that the natives are leaving the district for the mountain regions to the east. This migration of the population towards the highlands is general for the whole of Basutoland. Those districts including a higher proportion of the mountain regions are also those that exhibit the greater increases of population. It is evident that this migration is controlled by climatic conditions and area for cultivation. In these higher altitudes most of the population are concentrating on the 7,500 ft. peneplain, as is witnessed at Simonkong and Mokhotlong. It is doubtful if much cultivation will ever be undertaken above 8,000 feet. Above this limit the mountain regions are devoted to grazing.

Geological Succession and Structure

The rocks outcropping in Basutoland belong for the main part to the Karroo System, more especially to the Stormberg Series, which forms the uppermost beds of the Karroo. The Upper Beaufort Beds underlying the Stormberg are exposed in small inliers and in the vicinity of the Caledon River in the lower portions of the western lowlands. The Stormberg Series comprise (*a*) Molteno Beds, (*b*) Red Beds, (*c*) Cave Sandstone, and (*d*) Drakensberg Beds. The lower three are sediments and the Drakensberg consist largely of a monotonous series of basalt flows, about 4,500 feet thick.

In age the Karroo rocks range from Carboniferous to Rhaetic or later: the age of the Stormberg sediments is Triassic to Rhaetic and the lavas are usually assigned to Lower Jurassic. Throughout the whole world these strata are characterized by a peculiar reptilian fauna. The super-order of Dinosaurs made their first appearance in Middle Triassic times, but the flora is confined to ferns, horsetails, and cycads. In South Africa, however, a peculiar flora of Pteridosperms, the *Thinnfeldia* flora, first appears in the Upper Beaufort and flourished chiefly in Molteno times.

The mapping of the various beds shows that only a fraction of Basutoland is occupied by the sediments. Molteno Beds outcrop extensively in the western portions of Maseru, Mafeteng, and Mohale's Hoek districts. Narrow outcrops are seen in the northern districts close to the Caledon River and some of its main tributary streams. Red Beds overlie conformably and form the intervening slopes from the krantzes of the Molteno grits to the steep cliffs of Cave Sandstone. The Cave Sandstone is recognized by the dead-white, cream-coloured, or chalky-white massive sandstone which underlies the black basalt. The dips of the strata rarely rise above 5°, and in many areas the beds are horizontal. Nevertheless there is a slight undulation of the beds and small slightly arched domes were recorded. In the northern districts there are inliers of Upper Beaufort Beds mapped at several points. An inlier of Molteno Beds was noted on the borders of Mohale's Hoek and Quthing districts. The majority of the low domes and basins are due to the result of the crossing of two sets of folds at right angles to each other, the axes of which follow N.E. and N.W. directions.

Faulting is not very common. An excellent example is that observed between Thaba Tsueu and Hellspoort in Mafeteng district. At this point there is a throw of 1,000 feet. The fault may be traced in a N.E. direction towards Ralekika's and the Seketliseng valley in Maseru district. It was followed in a S.W. direction to the Orange Free State boundary at the southern end of the Mahadinyane hills. Near Ralekika's the throw was calculated at 600 feet. The downthrow is to the south-east. At Hellspoort the contrast between the rocks on the two sides of the fault is especially striking. On the Mafeteng side Molteno grits lie side by side with uppermost Red Beds. Cave Sandstone and overlying basalt on Thabana Morena plateau occur at a much lower level than the same rocks on Thaba Tsueu. The Cave Sandstone inliers at Ralekika's and Seketliseng valley have sharp faulted eastern boundaries. Another striking example is that seen in the upper Quthing River valley close to Mosikolelo's village. In this case Red Beds are faulted against basalt and Cave Sandstone. The throw is 660 feet to the north. As a consequence of the fault the Quthing River valley widens out from the narrow gorge into a broad valley. An important fault is that which strikes in a north-west by west direction from south of Sikaki's Store, in Qacha's Nek district, to the Cinquyane River near Nkau. The downthrow of 400 feet is to the south. Another fault cuts it diagonally close to Muse village and for a certain distance a dolerite dyke has followed the fault plane. The throw of the second fault is 420 feet to the south-west. At Ntho's village, to the north-west of Nthodimonate Mountain, Cave Sandstone is disrupted by a small strike fault. It has a general north-west direction and the beds are repeated. The throw is about 200 feet to the north-east. The repetition of beds is responsible for the wide expanse of Cave Sandstone in this area. Minor faulting was noted at several localities and it is evident that minor dislocations also occur close to many dolerite dykes the sides of which are often slickensided.

STRATIGRAPHY OF THE STORMBERG SEDIMENTS

A study of a large number of sections reveals that there are certain not unexpected conclusions of considerable interest to students of Karroo geology.

The Molteno Beds in Basutoland may be divided into two contrasting facies, a northern, which consists of a single unit of grits, and a southern, which, thicker than the northern beds, includes thick argillaceous members. The characteristic feature of the Molteno Beds exposed in the north is the almost constant uniform thickness and the unchanging nature of the sediments. The rocks are coarse felspathic sandstones or arkosic grits or both. Locally, however, these arenaceous beds include lenses of bluish-grey shales or mudstones and black carbonaceous shales. In the carbonaceous shales fragments of carbonized plants were invariably found in thin seams or streaks matted together. In the mudstones carbonized plant-fragments were commonly present. At a number of localities both the shale and the coaly material has become pyritized. Incomplete fern fronds were found at most localities.

The arkosic grits not uncommonly contain comminuted carbonized plant-fragments, carbonized wood blocks, coaly detached pieces, and thin impersistent coaly streaks or seams, parts of which may be pyritized. A thin section of the grits shows that the felspars, chiefly microcline, are fresh and water-clear. The grains are sub-angular to angular in outline : but a few are rounded. Many of these pebbles measure 6 to 9 inches in diameter : they are quartzites and quartz derived from pre-Karroo formations. Silicified wood, *Dadoxylon* sp., is commonly associated with these rocks : it was observed in situ in a number of cases. In addition sandstone casts after wood were everywhere seen in one or another horizon of the grits. This feature was specially remarked in the southern facies.

In the vicinity of Matsieng and Masite Nek limonitic grits and conglomeratic grits contain blocks of silicified wood lying with their lengths parallel to the bedding planes. Another feature of the grits and coarse felspathic sandstones is the current-bedding : most of the sandstones sparkle in sunlight owing to reflection of light from the faces of quartz crystals, hence the appropriate term "glittering sandstone" applied to them. Rounded nodules of pyrite or marcasite are found in these grits, but in many cases the sulphides are oxidized to limonite. In a section near Kolo Mountain pyrite cubes were found in the quartzite pebbles replacing the rock and thin seams of pyrite were noted replacing the grits and sandstone. Coaly patches, though not entirely absent in the south-western districts, are much less common than in those of the north. Carbonized wood fragments and coaly streaks were seen in the mudstones and shales, but carbonaceous flakes were more infrequent in the grits and sandstones.

Clay-pellet conglomerates are a common feature of all the sandstones and grits. In certain cases the clay-pellets are replaced by limonite, indicating original sulphide replacement. Kaolin bands were also observed in a few sections.

In only one case were red shales observed in the Molteno sequence, but in Mafeteng district a coarse arkosic grit, underlain by either red shales or mudstones, divides the uppermost Molteno Beds from the Red Beds above. But in no other cases were purple or red shales or mudstones found in the Molteno Beds. The dominant colours of the argillaceous beds are grey, bluish-grey, blue, or greyish-green.

Both the Molteno Beds and the Red Beds thicken out from the north to the south and south-west. Molteno Beds in the northern districts have a uniform thickness of 100 to 160 feet, but in S.W. Maseru district the Molteno Beds have thickened to 300 to 450 feet: in Mafeteng and Mohale's Hoek districts they are as much as 500 feet thick and more.

The junction between the underlying Molteno Beds and Red Beds is usually sharply defined. The evidence gained indicated that everywhere in Basutoland the contact cannot be considered other than conformable. In the northern districts there is little difficulty in determining the boundary, for the Molteno Beds outcrop as cliffs or bluffs in many of the tributaries of the Machaneng and Caledon rivers and the boundary line may be drawn a little distance away from the steep profiles, showing the Molteno Beds as narrow strips on the geological map. In the southern districts, however, there is a little uncertainty in drawing the boundary line between the two formations owing to the presence of a white arkosic grit at the base of the Red Beds, a bed which is remarkably like the typical Molteno grits. In the north-western districts Red Beds vary from approximately 100 to 250 feet in thickness. They are 200 feet thick in Northern Berea district, but they thicken to 320 feet in Western Berea. In Maseru district they are as much as 400 to 500 feet thick: they rapidly increase in Mohale's Hoek and Quthing districts where they attain a thickness of 700 to 800 feet. Near Blue Gum's Store Red Beds must be almost 1,000 feet in thickness.

Red Beds consist of red, purple-red, and purple mudstones, shales, and fine-grained sandstones, which alternate with buff sandstones. The red colour of the fine-grained sediments is not limited to weathered portions, but it is the actual colour of the rock: the ferric oxide, responsible for the bright colours, was deposited contemporaneously with the sand or mud as the case may be. Many of the sandstones are felspathic and there is a tendency to coarse and gritty types at the base, so that there is often considerable difficulty in determining the actual junction between Red Beds and Molteno Beds. Many of the sandstones are calcareous and these calcareous facies are commonly ossiferous. Silicified wood weathers out as detached blocks, but fragments observable *in situ* are rare.

The dividing line between Red Beds and Cave Sandstone is not sharply defined. During the survey considerable difficulty was encountered in determining the exact junction between the two formations. The writer was guided by the work of Van Eeden (1937) for the northern districts and by that of du Toit (1904) for the southern boundary regions. In practice for mapping purposes the boundary line can be considered accurately drawn, for the junction invariably occurs in cliff sections. As Van Eeden remarks (p. 25) :—

> " The Red Beds proper grade into fine-grained sandstones, mudstones, and shales, red and purple in colour. These again grade into red massive fine-grained sandstone, followed by the typical yellowish, massive fine-grained sandstone of the Cave Sandstone. The colour is no criterion for fixing the dividing line."

As a rule there is a buff sandstone, coarse to medium-grained, which overlies a thick bed of bright-coloured mudstones and shales, and underlies either pink, red, or purplish-red fine-grained sandstone at the base of the Cave Sandstone.

The writer has followed Van Eeden in his division of the Cave Sandstone into *transition beds* and the *massive sandstone*. The latter makes a conspicuous feature in Basutoland. It is largely responsible for the dead-white cliffs of the elevated plateaus, such as Qeme in Maseru district and the Leribe and Berea plateaus ; and the steep chalky-white gorges, several hundreds of feet deep, of all the main rivers of Basutoland. The massive sandstone is usually unbedded, but aeolian cross bedding is a common feature. It is very uniform in texture : it may be bedded either in its uppermost portion or towards its base or both. As in the Red Beds calcareous nodules are common especially in the lower fine-grained red sandstone.

The Cave Sandstone in the northern districts has a uniform thickness of about 400 feet. Transition beds for the most part are absent in the north : they are best exposed in the Southern

Leribe district, in Maseru and Mafeteng districts. In the latter two districts the average thickness is 500 to 600 feet. In Mohale's Hoek district the Cave Sandstone thins down to about 150 feet in the vicinity of Kornet Spruit and of the administration station, but above Blue Gum's Store it is again approximately 600 feet composed of massive cream-coloured, fine-grained sandstones in the upper portion, and pinkish sandstone overlying the Red Beds. The Cave Sandstone again thins out in the area of Moyeni and Simpi's, in Quthing district. Close to Fort Hartley Store overlooking Kabe's village, it is no more than 100 feet thick, but it rapidly thickens upstream in the Orange River valley, where its maximum is 1,000 feet between Mohlakwana and Kubung Stores. In this area the scenery is both awful and magnificent: the high white cliffs and vertical columns of Cave Sandstone, overlain by black basalt, give an imposing appearance.

Having reviewed the main characters of the sediments, the conditions under which these rocks were formed may now be discussed. That the Molteno Beds were laid down in shallow water under climatic conditions of intermittent rainfall is proved by the nature of the sediments and the fossils entombed within them. The thinning of the beds from south to north, the increasing coarseness and arenaceous nature southwards, and the increasing occurrence of conglomerates composed of smooth rounded quartzites derived from pre-Karroo rocks, suggest that the direction of the source of the material was from the south and south-east. It is supposed that these sediments were laid down at the foot of a range of mountains in the form of a fan. As Haughton (1924) points out :—

> "The absence of red sediments and calcareous sediments precludes the possibility of any arid or very dry intervals.
>
> "The abundance of felspar in the sandstones proves that decomposition was not very complete, and argues a somewhat cool climate with discontinuous rainfall. The presence of boulders and pebbles can be explained by occasional torrential downpours following on periods of comparative quiescence in which vegetation was able to flourish.
>
> "The nature of the coal seams and of the fossil plants associated therewith, is of considerable interest . . . the often perfect preservation of the plants which are mainly delicate and fragile fronds of ferns and fern-allies, precludes the possibility of their having been transported far from their place of growth by river torrents. There is little or no maceration shown by the fossils, except occasionally in the sandstones, and it is more reasonable to suppose that the plants were buried near to the swamps in which they grew and flourished.
>
> "Such swamps occupied discontinuous areas in the region ; for although contemporaneous erosion is the explanation of the lack of coal seams in certain parts, their absence in others is most likely due to an original absence of swampy ground. Such discontinuity in swamp conditions is a feature of flood-plain in an intermittently rainy climate rather than in continuously rainy regions. . . . During the former, and following it, vegetation temporarily

springs up, withers, and gives place to desert conditions until the next flood. Such alternation would possibly result in thin coal seams in thin sandstones and shales; but conditions of too great dryness would not be favourable to the formation and preservation of plant fossils."

Thus the lenses of carbonaceous shales, known in certain localities of the western districts, represent the sites of original swamps or vleis situated on the slightly inclined slopes or plains. The evidence also shows that these isolated swamps, were never very extensive and in the northern districts quite shallow.

The theory is generally accepted that a uniform red colour in sediments, unaccompanied by blue or green or black, and due to the presence of iron oxide precipitated contemporaneously with deposition, is indicative of an arid or semi-arid climate. In the Red Beds and the transition beds of the Cave Sandstone red colour naturally predominates, but the presence of medium-grained to coarse buff felspathic sandstones proves that semi-arid conditions at first alternated with arid. The fact that no traces of fossil plants or carbonaceous matter were found points to the possibility that the swamp conditions of Molteno times either had ceased or were in the process of cessation. These sediments also become finer and redder towards the top, while calcareous nodules and impersistent limestone bands are not uncommon. They are features consistent with increasing aridity.

The survey did not reveal any large fossil bone concentrations such as are known elsewhere in the Cape Province and the Orange Free State. Small bone fragments, however, are very common in the upper Red Beds, but very few determinable bones were discovered. So far only the bones of *Massospondylus*, and of *Thecodontosaurus browni* (Seeley), and the mammal, *Tritylodon*, have been recognized from these beds.

The fine grain and angular shape of the sand (which includes fresh felspar and mica), the aeolian type of bedding, the massive uniform and unbedded nature, the general lack of fossil plants and bones, the presence of dreikanters in adjacent areas, suggest the general aridity prevailing at the time of the formation of the Cave Sandstone. Nevertheless in Basutoland, as elsewhere, there is some evidence that the climate was not absolutely arid. At four localities thin beds of grey or black shales containing the crustacean, *Cyzicus* (*Euestheria*) *draperi*, and some comminuted carbonized plant fragments were found. In addition it was not uncommon to find in the western and southern districts thin beds of red shale or mudstone, and the lower portion of the massive sandstone may be stained pale green, blue, or pink. At no other places were evidences of any life observed. At Phamong Hill, in Mohale's Hoek district opposite to Simp's, silicified wood was found embedded in the base of the lowermost lava flow. Presumably these blocks were picked up from the sand surface by the lava during its movement over the desert. The presence of thin green, red, and grey to black shales proves that temporarily minor swamps, vleis, or oases existed.

VOLCANICITY OF THE DRAKENSBERG BEDS

During the climatic changes from semi-humid to dry, volcanic eruptions began and continued through the early and middle Stormberg period. These perforations, though numerous, were of minor and local extent. Some seventy-two vents and diatremes were located in Basutoland and they were distributed throughout the lowlands in the following frequency of occurrence in the various districts :—

Butha Buthe	sub-district	4
Leribe	district	2
Berea	,,	1
Maseru	,,	3
Mafeteng	,,	10
Mohale's Hoek	,,	18
Qacha's Nek	,,	26
Quthing	,,	8

The distribution of the vents, as is implied in the above list, shows that there is a general concentration of the vents in the south and south-west, that is, in the direction of the thickening of the Molteno Beds. This is new evidence supporting the interesting theory, propounded by Gevers (1928), that the volcanic explosions took place not far below the Molteno Beds, possibly within them. (The writer is indebted to Dr. A. W. Rogers for a copy of Gevers's paper and for bringing it to his notice.)

Gevers shows that :—

> " The stratigraphical horizon forming the present surface has a direct bearing on (1) the number and size of the volcanic vents ; (2) the nature of the rock fillings ; (3) the abundance of dolerite and the frequency of any one particular kind of intrusion (dyke, thin sheet, thick sheet, etc.)."

Under (1) he was able to show that the greater number occur in the Upper Stormberg beds, especially in the Cave Sandstone and Red Beds. In Basutoland the figures show that six vents were located in the Drakensberg Beds, thirty-nine in Cave Sandstone, twenty-three in Red Beds, and only four in the Molteno Beds. None were found in the Upper Beaufort beds, another fact which Gevers had already pointed out. He also shows that their distribution is irregular :—

> " There is no evidence whatsoever of their being arranged along definite pre-existing tectonic lines. On the contrary, they have a tendency to occur in clusters."

The work in Basutoland supports these observations. There are both individual vents and clusters, the former seeming to be located chiefly in the western lowlands and the latter in the south and south-east : between the region of individual vents and that of clusters there is an intervening region where the vents tend to occur in pairs, namely in the south-west. The clusters were found in the following groups : twelve at Sehlabathebe, four at Sehonghong River, eight at Mohlapiso's drift in Qacha's Nek district ; and four at Lampi (between Phamong and Nohana Store) in Mohale's Hoek district ; three near Moyeni in Quthing district ; and a group of three near Qhobela's in Butha Buthe sub-district. Vents occurring in pairs were noted at Phamong, Maputseng, Mohale's Hoek Camp, and at Tsoloane Store. Thus over 50 per cent of the vents and diatremes occur either in pairs or in groups of three or more.

As a rule the vents in the north-western districts are small, but those in Mohale's Hoek and Qacha's Nek districts are commonly large. It was also found that all the fragmental clastic material plugging the vents is derived wholly from the Red Beds and Cave Sandstone.

Gevers, while drawing attention to the connection between the vents and the dolerite sheets, says :—

> " It is a noteworthy fact in this connection that thick sheets of dolerite and kindred magma are practically limited to the central portion of the Karroo basin, and, what is more, to the Upper Beaufort beds or the base of the Molteno Beds."

In Basutoland it is noticeable that the thickest and most extensive sheets of dolerite occur at the Upper Beaufort-Molteno horizon. The western portion of Mafeteng district, especially that area north and north-west of Wepener, is a convincing instance. This sill was calculated as being 820 feet thick in the Peshela hills opposite Maputo's Store. To the south, opposite Tsakholo Store, it is about 550 feet thick. It thins out to the north ; to the south it persists into the Orange Free State. Subsidiary sills connected with this major sheet were recorded from Kolo Mountain, from south of Tsakholo Lake, and from Modise. Minor sheets in the same district and in the N.W. portion of Mohale's Hoek district commonly penetrate the Molteno Beds at various horizons. Observations showed that there is a progressive thinning and decreasing frequency of occurrence of dolerite sheets from the base of the Molteno Beds to the base of the Cave Sandstone. Even thin sheets of dolerite are exceedingly rare in the Cave Sandstone.

Mapping shows that dolerite dykes are so distributed that their numbers increase from east to west, that is from Cave Sandstone to Upper Beaufort Beds. This increasing frequency occurs in spite of the fact that the Cave Sandstone is for the greater part quite bare and relatively few dykes are concealed beneath the overburden. Many dykes cutting Red Beds and Molteno Beds are completely masked by a cover of eluvial deposits. Those dykes recorded from the lower beds thus constitute but a fraction of the actual total, whereas those noted in the Cave Sandstone represent an approximation to the whole.

It is generally considered by geologists in South Africa that the volcanicity of the Drakensberg took place at the close of the Triassic and the commencement of the Jurassic Epoch. The volcanicity may be divided into two stages ; an early explosive phase when innumerable perforations were drilled through the earth's crust and blew off the uppermost portion of the sand cover, and a subsequent quieter phase when the lava welled up through well-defined fissures, the infilling of which forms the dolerite dykes. The volcanic vents of the early phase were completely buried under the later sheets of basaltic lava. The lava overflowed and covered extensive areas, blanketing enormous stretches of country, far beyond the present surface of Basutoland. The lavas were apparently very mobile, for the numerous sections exposed in the gorges of the mountainous districts show that the flows are usually thin and extensive. At the base of each flow invariably there are pipe-amygdales separating the two flows. It is, therefore, evident that each successive flow followed closely after the upper surface of its predecessor had become chilled. There was no interval for erosion of the earlier flow.

The age of the faulting, previously referred to, is in every case post-Cave Sandstone and penecontemporaneous with the early Drakensberg volcanic outpourings. The faults die out in the basalts and are overlain by basalts. Thus the western extension of the Orange River fault near Nkau is completely obliterated in the upper basalt flows. The dislocation is limited to the lowermost flows. Furthermore, the fault planes are frequently traversed and followed by dolerite dykes.

Doubtless the early explosive action, concomitant with the liberation of gaseous accumulations in the shallow portions of the earth's crust, initiated these compensating movements. It is of interest to note that all the major fracturing and faulting in Basutoland is confined to the districts where there are the greatest concentrations of the volcanic vents. No serious faulting occurs in the north-western lowlands and very few volcanic necks and plugs are recorded from these districts. In the words of Gevers :—

> " This downward movement is best explained as being due to the removal of large masses of magmatic material by extrusion and the consequent collapse of the overlying strata."

PETROGRAPHICAL NOTES ON THE DRAKENSBERG LAVAS AND DOLERITES

In addition to the basalts which comprise the major proportion of the lava flows there are in the southern districts of Basutoland a number of agglomerates and ashy sandstones, which are included within the lower basalts. In the Seferong area on the borders of Qacha's Nek and Quthing districts, close to the Orange River, these pyroclastics overlie the Cave Sandstone, and they include the following beds :—

4. Sandstone overlain by basalt.
3. Agglomerate-tuff.
2. Cream-coloured well-bedded sandstone.
1. Pale grey agglomerate tuff.
   Cream-coloured Cave Sandstone.

The upper three beds together are not more than 10 feet thick ; the pale grey agglomerate-tuff measured 100 feet thick. Lower down the Orange River on both banks there are exposed a similar sequence of agglomerates and ashy sandstones overlying the lowermost basalt flow. The best outcrops occur in the Qwadi valley where the following succession was noted.

8. Basalt.
7. Ashy bed, 50 feet.
6. Tuffaceous sandstone, bedded, 100 feet.
5. Basalt flow, 100 feet.
4. Ashy beds, 50 feet.
3. Sandstone bed.
2. Purplish agglomerate bed.
1. Basalt flow.
   Cave Sandstone.

In one case the uppermost part of the Cave Sandstone became agglomeratic ; there was no distinct bed separating the aeolian sand from the mixed volcanic ejectamenta and the blown sand. Almost everywhere in Basutoland it is possible to find one or two thin sandstone beds overlying the lowermost basalt flows. In the upper Quthing River valley as many as six beds of sandstone occur intercalated between the lowermost lava flows.

Estimates of the thicknesses of the basalts were made at several points and these measurements show that no uniformity exists. On the Mashai Store track from the Sehonghong River in Qacha's Nek district fourteen successive flows were counted within a vertical interval of 1,200 feet, or an average thickness of 80 to 90 feet for each flow. Venter (1938) records 100 to 150 feet for each flow, from observations taken in the northern districts. Close to the junction of the Dinotsing and Mashai rivers six flows yielded an average thickness of 50 feet. In Butha Buthe district some 64 flows were counted on the track from the Khukune River to the summit of the mountain range, an interval of 3,500 feet, or an average figure of 55 feet per flow. On Qoqalasaning Hill, at the northern end of Leribe plateau, 26 flows were counted within a vertical interval of 450 feet, or an average of 15 feet per flow.

Thin sections from rocks collected from 53 different localities have been prepared and examined under the microscope. Of these 37 are straight basalts, 10 are olivine-basalts, 2 are andesites, 2 are oceanites, 1 is a trachyte, and 1 is a porphyritic (augite-rich) basalt.

The oceanites consist of rounded phenocrysts of fresh olivine set in a serpentinous base, which is completely lacking in felspars. Between the numerous olivine crystals are small granules or iron oxides and flakes of mica. In appearance these rocks are not very different from kimberlites. One specimen was collected from the S.W. side of Popanyane Hill in Maseru district and the other was picked up as a detached fragment, close to Malumeng in Mafeteng district, at the northern end of Thabana Morena plateau. The trachyte comes from Thaba Tsueu Hill in Mafeteng district. It is a pale greenish-grey amygdaloidal lava overlying the Cave Sandstone. Under the microscope it consists of laths of albite felspar in an opaque dirty-grey base: no pyroxenes are present.

In the vicinity of the north-eastern extension of the Thaba Tsueu fault, in the neighbourhood of Ralekika's and Kladi's Stores, a thick glassy basalt occurs at the base of the lavas. This rock consists almost wholly of palagonite glass, but laths of labradorite felspar and serpentinized olivine are not uncommon in some sections. Serpentine tracks traverse the rock in every direction and little vugs of brownish serpentine, calcite, and zeolitic minerals are also not infrequent. In the field, especially in the area of Ralekika's Store, this rock is well exposed. The whole lava has been much fractured and it contains many basaltic nodules or nuclei of crystallization. These nodules consist of fine microlaths of felspar in an opaque black base. The various stages from complete palagonite glass to the basaltic microcrystalline cores may be traced.

The two andesites come from Quthing district: they have already been described by du Toit (1904) but these rocks are of special interest because augite is absent and enstatite is the only pyroxenic mineral present.

There is very little difference between the lavas and dolerites both in texture and in the composition of the felspars and pyroxenes. The texture is usually ophitic to sub-ophitic; rarely is any directional flow indicated. It was possible, however, by selecting slides to grade them in a continuous series from the glassy basalt to those exhibiting doleritic texture. Most of the sections contain laths of fresh colourless labradorite felspar lying in all directions, in the interstices between which the pale brownish augite has crystallized. The proportion of these two minerals varies considerably, some of the specimens being more felspathic than others. In only one case the augite was found to have crystallized in well-shaped crystals forming phenocrysts. In many cases alteration of the pyroxene to bastite has taken place. In some cases there is a little basaltic glass. Amygdales infilled with zeolites, quartz, agate, calcite, chalcedony, and chlorite are very common. The chlorite is the vermicular variety fringing the inner edge of the vesicle. This mineral has been mistaken for oxidized copper ores.

Two samples of basalts collected from the heart of the Drakensberg mountains have been analysed. The complete analyses were undertaken by the Deputy Master of the Royal Mint, Pretoria. The first sample was collected by the writer from the upper Orange River above its junction with the Mokhotlong River, and the second was obtained by Venter (1938) from the Malibamatso River, near Thakabanna's cattle post.

From the data supplied by the analyses the normative composition has been calculated. A comparison of the two rocks brings out striking differences. The calculated mineral composition of the one sample contains 9 per cent of olivine, which is absent in the other. On the other hand, in the rock collected from the Malibamatso River, there is an excess of silica, amounting to as much as 6 per cent. The analysis of the same rock shows that there is as much as 5 per cent of water. It is probable that the presence of zeolitic minerals accounts for the high percentage of water and excess of silica, which in the mode are distributed partly amongst the hydrous silicates and also as either agate or quartz in the vesicles.

It is possible that these two samples represent more or less the two basaltic types already noted in the study of the thin sections: namely the olivine-free and the olivine-bearing basalts,

Constituent	Orange River (1) %	Maliba-matso (2) %	Minerals of Norm	(1) %	(2) %
SiO_2	49·45	48·63	Orthoclase	8·90	3·89
Al_2O_3	16·47	14·62	Albite	15·72	13·62
Fe_2O_3	2·27	4·97	Anorthite	31·97	30·58
FeO	8·23	5·81	Diopside	14·00	18·96
MgO	8·08	6·47	Hypersthene	14·70	14·87
CaO	10·12	10·69	Olivine	9·37	—
Na_2O	1·89	1·64	Magnetite	3·25	7·19
K_2O	1·47	0·64	Ilmenite	1·52	2·43
H_2O (+ 105° C.)	0·76	1·10	Apatite	0·51	0·34
H_2O (− 105° C.)	0·11	3·90	Quartz	—	6·00
TiO_2	0·82	1·25			
P_2O_5	0·24	0·21			
MnO	0·16	0·22			
CO_2	trace	0·01			
SO_3	0·02	—			
S	0·02	0·01			
Cr_2O_3	0·04	0·05			
CuO	0·01	0·01			
V_2O_3	nil	0·005			
NiO	nil	0·005			
BaO	nil	0·02			
Au and Ag	nil	—			
Total	100·16	100·26		99·94	97·88

and similarly the compact, in contrast with the amygdaloidal varieties.

Thirty-two thin sections of the dolerites have been examined under the microscope: of these, three were sliced from sills and the remainder from dykes. Of the total twenty contain olivine. It is true that the coarser and wider dykes are usually ophitic in texture and contain olivine in addition to the pyroxene. The narrower and basaltic dykes are usually intergranular and olivine is absent. The felspar in all cases is labradorite. Neither hypersthene nor enstatite was recognized in any slice, which seems to be a curious omission, for rhombic pyroxene is recorded from regions both to the south and north bordering on Basutoland.

The widest gabbroic dykes are located principally in the southern districts. A noteworthy example is that which crosses the territorial boundary 3 to 4 miles north-east of Qacha's Nek. It has a north-west by west direction and is 300 yards wide. It crosses the Orange River and makes for Mount Robinson, west of the Cinquyane River. This dyke was mapped along a distance of 37 miles. Other wide dykes were noted in the neighbourhood of Kubung and Nohana Stores, more especially near to the villages of Chalani and Daniele. Red Beds on both sides of these dykes are deeply blackened (lydianite) and vesicular. All the gabbroic dykes contain olivine. Other coarse and wide dykes worth noting are those trending almost east and west, just north of Mohale's Hoek administration station. It is possible that these two dykes are connected with those crossing the Orange River near Daniele in Quthing district.

Dolerite dykes trend in all directions, but the greater proportion strike either N.E. or N.W. or close approximations to those two directions. Quite a number have an equatorial direction.

South African geologists have recorded the fact that many dolerite dykes, as they enter the Drakensberg Beds, pass imperceptibly into lava flows. There was not time to corroborate in detail like instances in Basutoland, though the evidence collected seemed to substantiate this fact. In certain cases the extension of a dolerite passed into a weathered rock, which remarkably resembled the lava flows, but it was difficult to trace the pipe-amygdaloid base of the lava to the dolerite dyke fissure. Gevers (1928) states that in some cases dolerite dykes exhibit a change to vesicular types in the upper portion of the fissure.

In addition to the Karroo rocks a number of kimberlite pipes and fissures were recorded during the survey; reference to these rocks and other details will be found in the more comprehensive official report.

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Contact Metamorphism by a Tertiary Dyke at Waterfoot, Co. Antrim

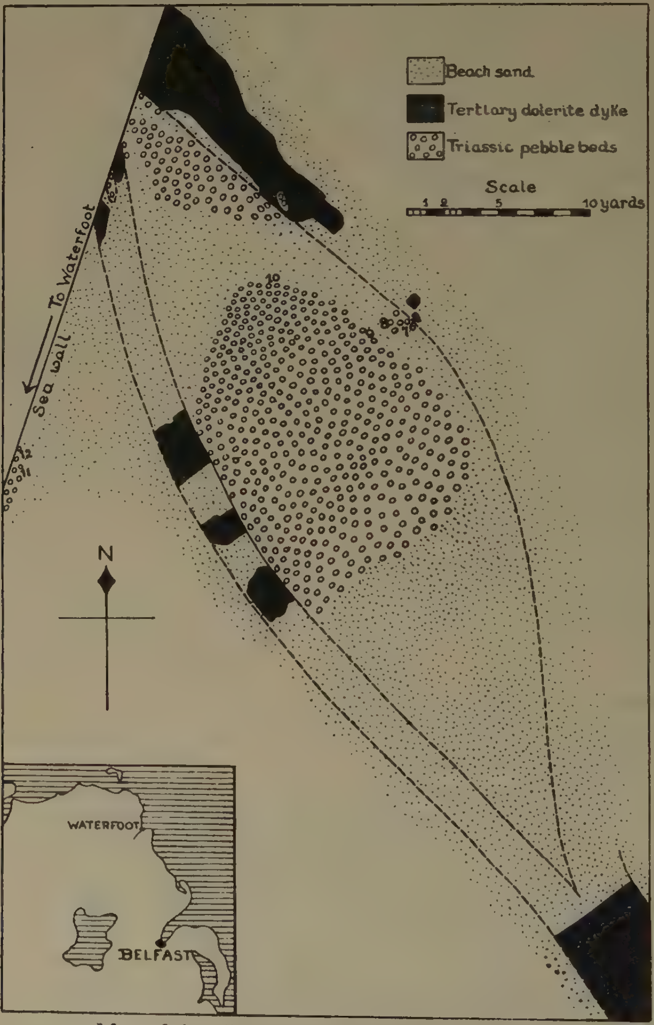
By Doris L. Reynolds (University of Durham)

CLOSE to Waterfoot and about one and a quarter miles south of Cushendall, in Co. Antrim, a bifurcating dolerite dyke of Tertiary age outcrops on the shore approximately 750 feet south-west of Red Bay pier (see text-fig. 1). The dyke is intruded into practically horizontal beds of Triassic sandstone which contain abundant fragments and pebbles of schist and quartzite. As shown on the map, text-fig. 1, the dyke bifurcates and encloses a lenticular portion of these Triassic beds. Where unaltered by the dyke, that is in the low cliff adjoining the sea-wall to the south-west of the dyke and in that portion of the enclosed mass adjoining the south-western branch of the dyke, the Trias is a friable yellow sandstone, rich in fragments of schist and quartzite ranging in size from a few inches down to microscopic dimensions. On the south-western side of the north-eastern branch of the dyke, however, a marked change takes place. The Trias here changes in colour from yellow to grey and becomes hard and compact; and, as the dyke is approached, the fragments and pebbles become less distinct and eventually merge into the matrix of the rock. This change begins between eight and nine feet from the contact. Within a foot from the contact the alteration is so intense that the main part of the rock has a compact homogeneous appearance, so that at first glance it resembles an igneous rock with sparse xenoliths of white quartzite. The schist fragments are here represented by dark patches which merge, often imperceptibly, into the matrix of the rock.

In order to determine the nature of the change that has taken place in the Triassic pebble beds a number of specimens were collected for microscopic examination. Care was taken to collect all the specimens from the same horizon, so that they should be directly comparable. At the same time specimens were collected from the dyke in order to see whether or not it shows any related marginal change. The positions from which the various specimens, to which reference is made, were collected are indicated on the map.

The Olivine-dolerite Dyke

The central part of the main dyke and of its north-eastern branch is olivine-dolerite like that of the North Star dyke, east of Ballycastle. It consists of purplish augite, labradorite, olivine, and abundant accessory iron-ore. The labradorite is sometimes zoned marginally to andesine, the range of composition being from An_{68} to An_{35}. The olivine has an almost straight isogyre in β-sections and is optically positive. Both augite and olivine show ophitic relationship towards the plagioclase. In the south-western branch of the dyke, and elsewhere at distances



TEXT-FIG. 1.—Map of the olivine-dolerite dyke near Waterfoot, Co. Antrim, as exposed in March, 1939.

of four feet and less from the margin, the olivine is serpentinized. The serpentine is fibrous, brownish in colour, with refractive indices lower than that of Canada balsam, and a medium birefringence. It is probably a variety of chrysotile (cf. Larsen's *Tables*). The purplish augite does not appear to change towards the margin and retains its large optic axial angle. Marginally, the rock becomes very fine grained and is characterized by a few relatively large crystals of plagioclase and serpentine pseudomorphs of olivine. The felspars in the marginal rock are partially replaced by serpentine with refractive indices lower than that of Canada balsam. The replacement is often restricted to a central or sub-peripheral zone. Towards the margin, tufted and radial aggregates of a bright green chlorite occur in the interstices of the rock; they decrease in abundance, however, in the central part of the dyke.

Amygdales, often of microscopic dimensions, are present in various parts of the dyke, and are filled with zeolite, chlorite, and calcite.

CONTACT METAMORPHISM OF THE TRIASSIC PEBBLE BEDS

(*a*) *Petrographical change.*

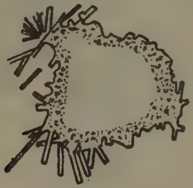
The sandy portion of the normal Triassic pebble beds which outcrop in the low cliff adjoining the sea wall to the south-west of the dyke is so friable that it had to be cemented by boiling in Canada balsam before thin sections could be prepared. Specimens 11 and 12, of friable yellow sandstone, are seen in thin section to consist of angular to sub-rounded grains of quartz and quartzite, dark coloured iron-rich grains which appear to be weathered relics of andesites derived from the local tuffaceous Old Red Sandstone, rarer greenish grains of mica-schist, sparse grains of microcline and rare rounded grains of garnet. A little biotite and muscovite are present as rare constituents within grains of quartzite. The interspaces between the grains are filled with calcite and a green chloritic mineral which varies in texture from cryptocrystalline to finely lamellar. The green mineral has refractive indices close to, and in part lower than, those of quartz, and a medium birefringence. The analysis of a similar sandstone, specimen 10 (see Table on page 468), indicates that this mineral is magnesium-rich and probably a variety of chlorite. The interstitial material forms a high percentage of the rock and in it the chloritic mineral is considerably more abundant than calcite.

Specimen 10 of the sandy part of the pebble beds, collected from the lenticular portion enclosed by the dyke, about nine feet from the north-eastern branch of the dyke, is as friable as the specimens just described and like them had to be cemented before sectioning. It differs from them macroscopically, however, in that it is greyer in colour. Microscopically, it resembles the specimens just described, but the section prepared from it contains, in addition to the constituents recorded above, rare grains of plagioclase, whilst the chloritic mineral is less strongly coloured.

Sections through schist fragments in the pebble beds, collected from the same locality as 10, show them to be composed of quartz, brown vermiculite, a little plagioclase, twig-like clusters of iron-ore granules, and accessory rounded grains of zircon, garnet, and apatite. The vermiculite, as seen in basal section, contains sagenite nets, and probably pseudomorphs biotite. It is pleochroic with X = nut brown ; Y = Z = deeper shade of brown. It has refractive indices lower than those of quartz and one lower than that of Canada balsam ; a medium birefringence ; a small optic axial angle, and is optically negative with X normal to the basal plane.

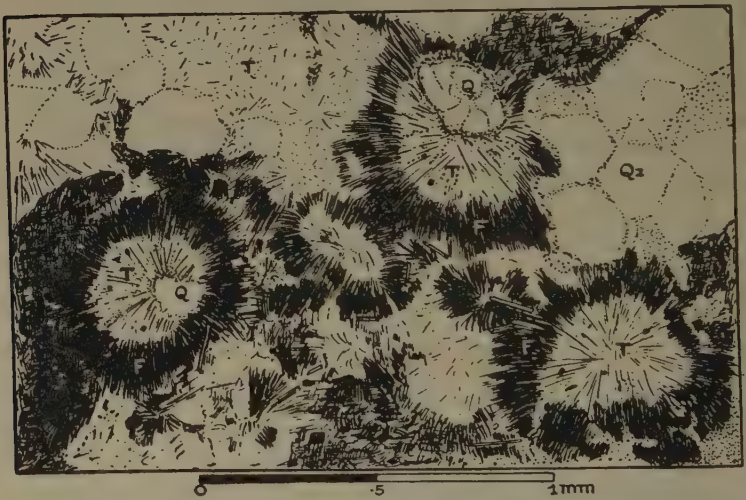
Specimens 9 and 8, six and three feet respectively from the contact with the north-eastern branch of the dyke, are hard grey compact rocks. The abundant pebbles and fragments of quartzite and schist which they contain exhibit sharp boundaries in the hand specimen. In section these specimens differ in several ways from those already described. A marked change has taken place in the interstitial material in which sand grains are embedded. Calcite has completely vanished, whilst clouds of exceedingly minute granules, with a strong relief, are seen to be associated with the chloritic mineral. When viewed with the high power, these granules are sometimes seen to be somewhat elongated and to show a high extinction angle with their length. They are probably monoclinic pyroxene, developed on metamorphism, due to reaction between the calcite and the chloritic mineral. Associated with the pyroxene granules and chlorite are grains of iron-ore and fine needles of rutile. The quartz grains have finely irregular (probably fritted) margins, and occasionally have a fringe of optically continuous spine-like projections that represent tridymite that has inverted to quartz. The andesite grains are represented by dark ghost-like patches, rich in minute granules of iron-ore, some of which merge into the rest of the rock, whilst others still retain their sharp outline. As seen under the microscope, the margins of the large composite grains and small pebbles have become indistinct, so that grains and pebbles appear to merge into the rest of the rock. The most striking change, however, has taken place in the schist fragments; in these the vermiculite is completely replaced by felsite. The felsite is brownish in colour and commonly spherulitic. A very striking appearance is presented by rows of small spherulites and imperfect elongated axiolites (representing vermiculite) embedded in a mosaic of quartz grains which retain their schistose elongation.

Specimens 7 and 6, collected six and four inches, respectively, from the dyke, show intense alteration. In the hand specimens they are compact rocks with a homogeneous appearance. In them a few quartz pebbles can still be discerned, whilst occasional relatively dark coloured patches, which merge into the rest of the rock, represent schist fragments. Under the microscope a very striking change is seen to have taken place in the interstitial material. Very little of the chlorite remains, its place being taken by brown felsite in which a tendency to a spherulitic texture is commonly discernible. Locally the fibres of the spherulites radiate out from the quartz grains, so that the latter form the centres of spherulites with a diameter of about 0·5 mm. Where the spherulitic rims adjoin the quartz grains they are dark brown in colour but, away from the quartz grains, they are margined by zones of lighter brown colour. When the felsite is interstitial only, with no regular disposition about the quartz grains, it often shows a sheaf-like development, but locally it is so fine as to be micro-aphanitic. Where the quartz grains adjoin the felsite they have outgrowths of quartz that are needle-like in section and are optically continuous with the grains (see text-fig. 2). The outgrowths are similar to, but finer grained and more numerous than, those of the tridymite fringes, paramorphed by quartz, which Thomas (1924, p. 274) has described around quartz in siliceous xenoliths from the tholeiite-andesite sills of the Loch Scridain area, Mull (slide 20283 of the Geological Survey collection). They may thus be taken to represent tridymite, formed during metamorphism, which later inverted



TEXT-FIG. 2.—A quartz grain fringed with quartz paramorphs of tridymite. The fringe is optically continuous with the grain. Scale as in text-fig. 3.

to quartz. Here and there, quartz grains are seen to be separated from their rimming spherulites by relatively broad colourless zones of radial prisms and needles of quartz paramorphs of tridymite; the central quartz grain is often placed excentrically within this zone (see text-fig. 3). Sometimes, in spherulites of comparable size, no central quartz grain can be seen, so that spherulites of colourless needle-like quartz paramorphs of tridymite are margined by a brown spherulitic rim. Amongst the needle-like quartz aggregates, larger quartz individuals are



TEXT-FIG. 3.—Camera lucida drawing of spherulites composed of quartz paramorphing tridymite, and of felsite. The spherulites are developed from the marginal parts of quartz grains and the adjacent interstitial material. In the north-east of the field is part of a small quartzite pebble with strings of gas inclusions along the intergranular boundaries. Q = quartz. Qz = quartzite. T = quartz paramorphs of tridymite. F = felsite.

occasionally discernible which exhibit a fine lamellar twinning. Kuno (1933) has described indistinct striations, like albite lamellae, from cross sections of tridymite.

The presence of interstitial material, which possibly made an easy passage-way for fluxes, appears to have been essential for the development of tridymite, for there are no signs that tridymite has been formed within the quartz pebbles. Here, however, the intergranular boundaries have a grey shaded appearance. Under the high power this is found to be due to the presence of minute dots and rods of a dark material with which are associated what appear to be minute gas inclusions. Sometimes streams of such gas inclusions traverse quartz pebbles and occasionally terminate in a marginal embayment filled with felsitic material. In such instances the quartzite pebbles have the appearance of xenoliths frozen in igneous rocks whilst in process of solution. The quartzite pebbles are surrounded by " tridymite " fringes and rims of felsite in which the components have a radial arrangement. Fragments of schist with patches and strings of spherulitic material (representing vermiculite) are still recognizable, but they fade out imperceptibly into the rest of the rock. Rounded aggregates of fine grained, clear plagioclase probably represent recrystallized andesite grains.

Pyroxene granules occur interstitially in specimens 7 and 6, as in specimens 9 and 8 previously described, but the granules are here a little larger in size and occur in more compact groups. They sometimes have a little of the green chloritic material associated with them. In addition, small yellowish green crystals of pyroxene are locally embedded in the felsite. They are euhedral, show oblique extinction, and are optically positive with 2V *ca* 50°. They are thus pigeonitic pyroxene. Scattered through the felsite and other interstitial materials are small octahedra of iron-ore. The grains of microcline and plagioclase, such as characterize the unaltered sandstone, have completely disappeared.

(*b*) *Chemical change.*

The development of felsite from vermiculite in the schist fragments, and from chloritic material present in the interstices of the sandstone, indicates that there has been a considerable migration of alkalies within the rock. The alkalies were no doubt partly supplied by the breakdown of grains of felspar originally present in the sandstone. The relative abundance of felsitic material, however, as compared with grains of felspar in the unaltered sandstone, suggested that there has actually been a chemical change and that alkalies were introduced into the rock on metamorphism. In order to determine any chemical change, specimen 10, of unaltered friable sandstone, and specimen 6, of highly metamorphosed rock, were analysed. The results are set out in the adjoining table, together with the respective normative compositions.

To some extent the analyses are disappointing, for most of the differences between them are such as could well be explained as original differences to be expected between any two adjoining specimens of sedimentary origin. There is, however, a marked

TABLE OF ANALYSES

	10	6
SiO_2	70·62	75·86
Al_2O_3	5·72	6·37
Fe_2O_3	1·48	1·47
FeO	1·32	1·76
MgO	4·11	4·32
CaO	5·74	3·61
Na_2O	·84	·79
K_2O	1·74	2·52
$H_2O +$	2·07	1·44
$H_2O -$	2·18	1·27
CO_2	3·81	none
TiO_2	·42	·62
P_2O_5	·13	·13
MnO	·01	tr.
	100·19	100·16

Normative composition		10	6
Quartz		51·16	49·66
Orthoclase		10·29	14·91
Albite		7·13	6·66
Anorthite		3·56	6·40
Corundum		1·14	—
Diopside	$CaSiO_3$	—	4·50
	$MgSiO_3$	—	3·61
	$FeSiO_3$	—	·36
Hypersthene	$MgSiO_3$	10·23	7·14
	$FeSiO_3$	·51	·63
Magnetite		2·15	2·13
Ilmenite		·80	1·18
Apatite		·30	·30
Calcite		8·66	—
Water		4·25	2·71
		100·18	100·19

10. Triassic sandstone, about nine feet from edge of dyke, south-west of Red Bay pier, Co. Antrim. *An.* W. H. Herdsman.

6. Metamorphosed Triassic sandstone (same horizon as No. 10), about four inches from edge of dyke. *An.* W. H. Herdsman.

increase in TiO_2 and K_2O in the metamorphosed specimen (6), whilst even more striking is the change in the alkali ratio. In the unaltered sandstone $K_2O/Na_2O = 2·1$, whilst in the metamorphosed rock it is 3·2 That chemical change has actually taken place is brought out more clearly, however, by comparison of the "norms" of the two rocks. Normative orthoclase shows a 45 per cent increase in the metamorphosed rock, despite the fact that the rock contains 5.24 per cent more silica than the unaltered sandstone. It can be safely concluded, therefore, that metamorphism of the pebble beds was accompanied by potash metasomatism.

CONCLUSION

The principal interest in this study lies in the fact that felsitic material, often with a spherulitic habit, and resembling felsite resultant on the rapid cooling of acid igneous material, has been developed in Triassic pebble beds, at their contact with a Tertiary dyke of olivine-dolerite, as a result of potash metasomatism at a temperature high enough for tridymite to form. The example has much in common with other examples of alkali metasomatism connected with the emplacement of basic Tertiary igneous rocks in north-east Ireland: e.g. the alteration of Caledonian granodiorite at its contacts with four gabbro masses in the Slieve Gullion area (Reynolds, 1937 and 1940); of granite inclusions in the Mourne dyke-swarm (Tomkeieff and Marshall, 1935); and of tuffaceous Old Red Sandstone at its contact with the olivine-dolerite plug of Tiveragh (Tomkeieff, 1940).

The changes that have taken place in the Triassic sandstone are closely similar to those described by Harker (1908 and 1939) from the Torridon sandstone in the Isle of Rum where it has been metamorphosed near intrusions of eucrite and peridotite. Tridymite, now represented by quartz, has developed from the quartz grains either as fringing growths or with a more dispersed arrangement, and, in places, a micrographic intergrowth of quartz and felspar has developed. Of these altered rocks Harker remarks: " except in the preponderance of quartz over felspar, some of these metamorphosed arkoses reproduce all the features of granophyres and spherulitic quartz-porphyries." Harker attributes the textural changes that have taken place in the Torridon sandstone to recrystallization of quartz and felspar. In view of the advance of knowledge since these observations were made in 1908, however, chemical analyses are now necessary before it can be decided whether this is, indeed, an example of straightforward recrystallization or one of metasomatism such as has been described in this paper.

ACKNOWLEDGMENTS

In conclusion the writer expresses her indebtedness and grateful thanks to the Research Fund Committee of the Council of the Durham Colleges for a grant out of which the cost of chemical analyses has been defrayed, and to the Officers of H.M. Geological Survey for the loan of thin sections.

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Glacial Drifts near Roslin, Midlothian

J. G. C. ANDERSON

(PLATE V)

INTRODUCTION

A RECENT examination of drift deposits south of Edinburgh has revealed the presence of boulder clay overlying fluvioglacial sands and gravels. This does not appear to have been the subject of any previous publication. The relevant exposures are almost entirely in working sandpits, and are liable to be obscured soon after the latter are abandoned. Accordingly it is thought worth while to place on record a description of the sections at present available for examination.

The sand-pits have been opened in the extensive sands and gravels of the Esk Valley. These deposits are shown in Sheet 32 [1] of the Geological Survey 1 inch to the mile map of Scotland, to which the reader is referred for localities mentioned in the present communication. The sands and gravels have been accepted as being of fluvioglacial origin. They overlie the widespread boulder clay which is the main product of the glaciation of the region. Purely for convenience of local description the latter may be referred to as the Lower Boulder Clay and the newly discovered deposit overlying the sands and gravels as the Upper Boulder Clay.

The Upper Boulder Clay was first noticed in pits south-west of Roslin, 6½ miles south by east of Edinburgh, and was later detected in others at Bilston, 5½ miles south by east of Edinburgh and Loanhead, 5¼ miles south-south-east of Edinburgh.

Novel views on the significance of glacial drifts, put forward in a paper [2] by Mr. R. G. Carruthers, have recently been discussed at length at a meeting of the Geological Society of London.

LOCAL DESCRIPTIONS

Oatslie Pit (Plate I).—This is a large opening high above the left bank of the River Esk about ½ mile south-west of Roslin and north of the farm of the same name. In the face of the pit 30–40 feet of sand with a few lenticular beds of gravel are seen. Current-bedding is developed on a spectacular scale. Capping the whole are from 6 to 10 feet of boulder clay, of a stiff, reddish type. Boulders are not particularly large or numerous but are sufficiently plentiful to render the deposit thoroughly typical. The junction between the boulder clay and the sand is quite sharp; no sign of disturbance could be detected in the bedding of the sand. At the north end of the quarry the ground falls away and the boulder clay follows the slope, cutting across the bedding-planes of the fluvioglacial deposits.

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[1] Drift Edition, published 1928.

[2] " On Northern Glacial Drifts : some Peculiarities and their Significance." *Quart. Jour. Geol. Soc.*, xcv, 1939, 299–333.

Roslin Pits.—These lie to the north-east of Oatslie Pit nearer the village, but on the same side of the River Esk. They are three in number; at the time of writing only the two southernmost were being worked. In all three pits boulder clay, 3 to 10 feet thick and similar to that in the Oatslie Pit, overlies the sands and gravels. In the middle pit bedded stoneless clay 1 to 2 feet thick intervenes between the sand and the boulder clay. Separating this pit and the one to the south there is a deep hollow, the sides of which have been quarried away to some extent. This feature has clearly been eroded through the fluvioglacial deposits. Its sides are lined with boulder clay which transgresses the bedding of the sand.

Analyses were made of the larger pebbles (over 2 inches) in the gravel and of the boulders in the overlying boulder clay (Table I). It will be noted that the vast majority are igneous rocks, many of types common in the neighbouring Pentland Hills, and Devonian and Carboniferous sedimentary rocks, along with a small number of stones of Highland origin. Southern Upland greywackes are rare and the few present might well have been derived from the Pentland Hills. The analyses from

TABLE I

	Gravel. %	*Boulder Clay.* %
Andesite . . .	12	14
Basalt . . .	7½	4½
Felsite . . .	24	14½
Volcanic Ash . .	1	1½
Red Sandstone . .	10	14
Other Sandstone .	28	40½
Limestone, Coal, and Blaes . . .	3	4½
Greywacke . .	3½	1
Quartzite . . .	1½	1
Vein-quartz . .	7½	4½
Diorite and granite .	2	0
	100	100

the two types of deposits are closely comparable, the greater proportion of hard igneous rocks in the gravel being what would be expected in a sediment which has been subjected to a certain amount of water transport.

Bilston Pit.—This is an extensive shallow opening a short distance south of Bilston, in the angle between the roads to Penicuik and Roslin. Sand with subordinate gravel beds and coaly layers is worked, overlain by some 4 to 6 feet of stiff red boulder clay, in which stones of moderate size are fairly plentiful. The most significant exposure is seen at the northern end. Here a vertical fissure in the sand, about 6 feet deep, and 2½ feet wide at the top, tapering downwards, is filled with the Upper Boulder Clay. The bedding of the sand near the sides of the fissure shows contortion and obscure faulting as if the sands had been slipping slightly at one time into the crack. Near by are several other fissures, not so deep, also filled with the Upper Boulder Clay. According to a note by my colleague Dr. T. Robertson on a MS. map a large boulder clay-filled pocket was exposed in the Bilston Pit in 1936.

Niven's Knowe.—This is an old pit on the west side of the main road, ⅜ mile north of Bilston. Its sides are now somewhat obscured by slipping, but from 2 to 6 feet of boulder clay can be seen overlying sand. A particularly clear section occurs at its northern end, showing a sharp junction between the two deposits.

Loanhead Pit.—This pit is situated on the west side of the railway, ¼ mile south-west of Loanhead station. The material worked is almost entirely sand. About 2 feet of typical, stiff, reddish boulder clay covers the latter in nearly all parts of the quarry. At the south end the boulder clay fills a broad irregular hollow nearly 10 feet deep in the sand and at the north end a narrow fissure of about the same depth but only a foot across. In the same part of the pit small-scale normal faults are clearly shown up by coaly bands in the sand. The faults do not affect the junction with the Upper Boulder Clay.

Other Sections.—Pits in the sands and gravels were visited at Straiton, Wadingburn, and Hawthornden, all between 4½ and 6½ miles south by east to south-south-east of Edinburgh and at Penicuik, 8¾ miles south by west of Edinburgh, but in none was the Upper Boulder Clay detected. An old pit at Comiston, on the southern outskirts of Edinburgh, where A. C. Campbell and E. M. Anderson [1] recorded a huge erratic of andesite resting

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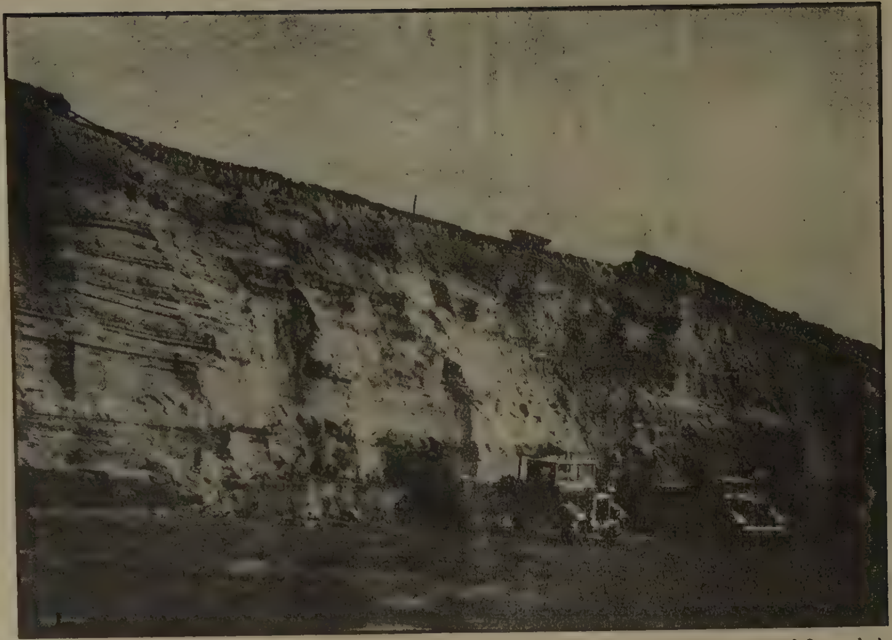
[1] "Notes on a Transported Mass of Igneous Rock at Comiston Sand-pit, near Edinburgh." *Trans. Edin. Geol. Soc.*, ix, 1909, 219.



(*Block loaned by Institute of Quarrying*)

OATSLIE SAND-PIT, NEAR ROSLIN, MIDLOTHIAN. BOULDER CLAY CAPPING
FLUVIOGLACIAL SANDS

on sands and gravels, was also inspected. The section is now much obscured. Clay with stones is, however, described as associated with the erratic; the latter it is now suggested may be regarded as a gigantic boulder in Upper Boulder Clay.

Natural sections, such as those of Bilston Burn, were found to be too much hidden by slipping and vegetation to afford an opportunity of detecting the Upper Boulder Clay.

The only other evidence obtained was from a bore near Roslin. This shows 12 feet of Upper Boulder Clay above 29 feet of sand on 7½ feet of Lower Boulder Clay overlying rock-head.

CONCLUSION

The pits in which the Upper Boulder Clay is seen are enclosed within an area of between 2½ and 3 square miles. If exposures were available doubtless other examples would be found. Within this area the Upper Boulder Clay must be regarded as definitely later than the fluvioglacial deposits it overlies. This view seems inescapable on considering the boulder clay-filled fissures at Bilston and Loanhead and the boulder clay-lined channel eroded through the sands at Roslin.

As the Upper Boulder Clay is thoroughly typical in nature, with none of the characteristics of a water-borne deposit, it must have been formed as the ground-moraine of ice readvancing over sands and gravels left bare by previously retreating ice and subjected to local denudation. The absence of contortion in the underlying sand can be ascribed to severe freezing. In fact it is only under such conditions that fissures could form in loose sand and stay open long enough to become filled with boulder clay.

Some of the pits were visited during the great frost of the early part of 1940. The sands, where stripped of the Upper Boulder Clay prior to digging, were seen to be frozen to a depth of several feet and to have the solidity of a Carboniferous sandstone. Blocks which had fallen to the quarry floor could be split with a hammer much like a block of rock.

Consideration of the nature and extent of the readvance responsible for the Upper Boulder Clay cannot be attempted in the present communication. It is hoped, however, that information on these points will result from a more general re-examination of the glacial phenomena of the Edinburgh district.

Notes on a large Spiriferoid from the Southern Shan States

By F. R. Cowper Reed

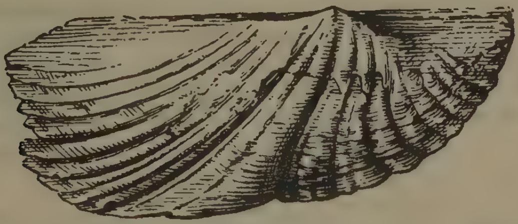
At a locality about three miles south of Mawchi, in the Kantarawaddy State, a unique specimen of a large Spiriferoid was found a few years ago by Mr. Vernon Hobson, then working for the Mawchi Mines Co., in an area where previously no fossiliferous rocks were known to exist. This specimen was sent me by him in 1936 for determination; and in the hope that some other fossils would soon be obtained from this locality which would throw more light on the age of the rocks, the publication of any description of the fossil was postponed. For unfortunately, the specimen was not found in situ, though Mr. Vernon Hobson, in a letter to me dated 19th June, 1936, stated that he was satisfied that it was not a residual fossil, and that the rock-matrix in which it is imbedded was thoroughly typical of the beds developed for miles round in this area. Moreover, he stated that there are no overlying formations within twelve miles, and that these lie at lower elevations, while pendants of younger rocks do not occur in the area, so that " there is no evidence that overlying rocks existed close above [the present surface rocks] prior to the present phase of erosion ".

Moreover, the state of the rock fragment containing the fossil does not show the rounding and abrasion of the edges on surface such as transportation by water from a distance would cause, and it is difficult to understand what other agency could have brought it to the place where it was found. No other fossils have been so far discovered at or near the place.

The rock containing the specimen is a heavy compact, fine-grained, dark-purplish, ferruginous flaggy sandstone, and it has suffered some crushing. The series of rocks in the area is termed by Mr. Hobson the " Mawchi Series ", and appears to belong to the Mergui Series which Dr. Coggin Brown (*Mem. Geol. Surv. India*, 1923, vol. xliv, pt. 2, p. 180) suggested was of Pre-Cambrian age, with the proviso that the series might be as late as older Palaeozoic. Mr. Sethu Rama Rau (*Mem. Geol. Surv.*, 1930, vol. lv, pt. 1, p. 14) tentatively correlated the beds with the Chaung Magyi Series (La Touche, 1913, *Mem. Geol. Surv. India*, vol. xxxix, pt. 2, pp. 47–55) of the Northern Shan States which were doubtfully also referred to the Pre-Cambrian, though it was again remarked that in part they were possibly older

Palaeozoic. Unfortunately, no organic remains have been found in situ anywhere in the Mergui or Chaung Magyi Series.

Our present specimen, which is somewhat crushed and obliquely distorted, consists of a nearly perfect cast of a brachial valve, with a small portion of the shell attached near the hinge-line. It has a transversely semi-elliptical shape with a long straight hinge-line, rectangular or subrectangular cardinal angles (of which only the right one is unbroken), and a small low umbo scarcely rising above the hinge-line. There is a broad, smooth, median fold expanding rather rapidly towards its anterior end, and bearing a faint narrow median groove; it rises gently above the lateral lobes from which it is separated by rather strong deep grooves. The lateral lobes of the specimen are unequally compressed and distorted, so that they have a completely different appearance, the right lobe being laterally stretched and antero-posteriorly compressed, while the left lobe has suffered much oblique compression from the outer side. The right lobe possesses 7–8 low rounded ribs, of which the first three broaden rather rapidly to the margin; the one adjoining the median fold of the valve is apparently grooved nearly down the middle in its distal half, and the second one likewise; the third, fourth, and remaining three or four ribs are simple, but rapidly decrease in size and strength towards the cardinal angle, where they become indistinct. The ribs on the left lobe of the valve are all obliquely squeezed together so as to appear much narrower and more equal in size, but the one adjoining the median fold seems to be triplicate and to consist of three specially narrow ones arising from a single stem near the umbo, though this may be due to the crushing and distortion which the specimen has suffered.



On the right lobe the ribs are crossed by strong closely placed concentric sublamellose lines or very narrow low rounded linear rugae, and the same are traceable on parts of the median fold, but there is no sign of them on the left lobe; they seem, however, to be an original character of the shell-surface, and not due to any crushing or crumpling which it subsequently received.

The true dimensions of the shell are hard to determine accurately, on account of its crushed and distorted condition, but it may be estimated to have had a length of about 35 mm. and a width along the hinge-line of about 60 mm. or rather more.

As regards its relations, it may most probably be referred to some species of *Syringothyris* or *Pseudosyrinx*, and to be related, though not closely, to the Carboniferous species *Syringothyris cuspidata* (Martin), which Diener described and figured from the Syringothyris Limestone of Kashmir (1899, pl. iv, figs. 9, 10 ; 1915, p. 9, pl. i, figs. 6–8). But the species from the Agglomeratic State of Kashmir described by Bion as *Spirifer nagmarensis* (1928, pp. 27, 38, pl. ii, figs. 2–5 ; pl. iv, fig. 15), but put by the present author in the genus *Syringothyris*, seems to be rather like it (Reed, 1932, p. 25, pl. vi, figs. 1–4). Licharew (1934, pp. 67, 122, t. ii, figs. 1, 2, 6 ; t. iii, figs. 1–5, 7) considers the Russian species *Pseudosyrinx kolymaensis* (Tolmatscheff) to be allied to that Kashmir species of Lower Permian or Upper Carboniferous age, and he further discusses the affinities of that species in describing examples from Novaya Zemlya (Licharew and Einor, 1939, p. 159, t. xxvii, fig. 2 ; t. xxviii, fig. 1), referring to its resemblance to *Syringothyris spitzbergensis* Wiman (1914, p. 51, t. viii, figs. 5–7) and to *Spirifer tastubensis* Tschern. ? as figured and described also by Wiman (1914, p. 45, t. vii, figs. 5–8) which especially resembles our specimen ; *Sp. loveni* Wiman (1914, p. 50, t. vii, figs. 12–13 ; t. viii, figs. 1–4) is another allied Spitzbergen species.

We may certainly observe that as far as the external characters of the brachial valve indicate our specimen shows a considerable similarity to *Ps. kolymaensis*. Mansuy's example (1913, p. 60, pl. v, fig. 8*a–c*) of *Sp. tastubensis* from the *Schwagerina princeps* horizon of the Productus Limestone in Indo-China resembles it less though he considered that specimen as closely resembling *Spirifer lydekkeri* Diener from the Fenestella shales of Kashmir, which its author later (1915, p. 38, pl. iv, figs. 3–6) removed to the genus *Syringothyris*. *Syr. lydekkeri* has, however, many more ribs on the lateral lobes, as Mansuy (1912, p. 41, pl. viii, fig. 9) had previously figured in an example from Laos, and it is more closely allied to *Syr. cuspidata* than to *Sp. tastubensis* or our specimen. Probably *Sp. tastubensis* belongs to *Syringothyris* or *Pseudosyrinx* rather than to *Spirifer* as Licharew and Mansuy seem inclined to believe. We may mention that *Sp. schellwieni*

Tschern. (1902, pp. 149, 536, pl. ix, figs. 4, 5) which appears to be allied has been recently placed by Heritsch (1938, p. 132) in the genus *Pseudosyrinx*.

None of the British varieties of *Syr. cuspidata* described by North (1920, pp. 165–189, pls. xi, xii) or its allied species appear to approach our fossil as closely in character as the Russian species, *Sp. tastubensis* and *Ps. kolymaensis*. But as we do not know its internal characters its precise generic reference is doubtful, though on the whole we may provisionally consider that it should be placed either in the genus *Syringothyris* or *Pseudosyrinx* rather than in *Spirifer*. We may remark that no similar brachiopod has so far been found in the Anthracolithic series of the Shan States and that the lithological character of the rock in which this specimen occurs is quite distinct to that in which the fauna of that formation is preserved in that region so far as it is known.

If the tentative reference of this fossil to *Syringothyris* or *Pseudosyrinx* is correct, we may suspect that somewhat lower beds of Permo-Carboniferous age occur in the vicinity than any previously determined.

My thanks are due to the Directors of the Mawchi Mines for permission to publish this communication.

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Phenol Formaldehyde Resin as a Casting Material

By W. F. Whittard and J. E. Sisson

THE remarkable properties that synthetic resins possess make these substances of inestimable value in biological and geological laboratories and museums. Their applications in the biological sciences have been discussed by Hibbin (1937) and by Knight (1937). Bell (1939) and Shrock (1940) have indicated some of the geological methods employing polymerized methyl methacrylate ; the material is remarkably transparent and this property tends to detract from the value of the plastic as a casting substance of fossils for, in such work, an opaque material is desirable.

Brachiopod casts present difficulties not commonly encountered in similarly preserved fossils of many other animal groups, the teeth, cardinalia, and associated structures being represented by narrow cavities which invariably enlarge inwards and are of complicated shape. Materials such as plasticine, plastrone, gutta-percha, dental wax, and so forth are inelastic and, consequently, distort when extracted. Gelatine and similar substances tend to tear and are not permanent ; a solution of gelatine in glycerine provides an elastic medium but the fossil cast must be coated with shellac dissolved in 95 per cent alcohol and, when this is dry, a film of clove oil must be applied before an impression can be taken. Obviously, in most brachiopod casts, it is not possible to carry out these necessary preparations because the deeper seated portions cannot be reached. Rubber compounds, such as Airvulc Liquid Rubber and the mixture supplied by Revertex Co., Ltd., are elastic and give impressions showing the most minute detail but there is a tendency to shrinkage, particularly in the case of the latter. Since all the mentioned materials possess one disadvantage or another, we decided to try and find an inert plastic which was opaque and did not react with hydrofluoric acid ; the latter quality would permit the solution of the matrix in acid, thus giving an impression. Experiments were carried out with a special liquid phenol formaldehyde resin, to which had been added an acid catalyst to allow the resin to harden in situ to an inert solid. The impressions which have now been prepared exhibit all the surface detail and they thus serve nearly the same purposes for the palaeontologist as the original shells. The fossil admittedly is destroyed but, with the majority of brachiopods, more than one cast is available. The method permits the correlation and identification of internal casts with the interiors of actual shells. The plastic is opaque, hard, tough, and can be cut with a diamond armoured disc.

Method.—A glass ring is prepared, of a diameter and depth suitable to the specimen, coated on the inside with paraffin wax and placed on a small sheet of glass. Melted wax is poured into the ring and the specimen fixed down, with the surface carrying the internal cast uppermost. When set firm, more wax is poured in to the required level, the top surface of the matrix and its cast being left free of wax. The phenol formaldehyde resin used is Resin 414, which is supplied, with the required amount of catalyst, by I.C.I. (Plastics), Ltd., The Hall, Welwyn, Herts. The resin is thoroughly mixed with the acid hardener, in the proportion of ten parts by volume of resin to one part by volume of catalyst. If excess of catalyst is added, or if the temperature of the mixture is allowed to rise, the resin reacts too quickly, commences to froth, and hardens immediately, making it useless for casting purposes. If the resin is found to be too reactive or too viscous for the particular application, methylated spirit is added and thoroughly mixed in before the addition of the acid ; the amount of spirit added should be no greater than 2 per cent of the volume of the resin. As soon as the mixture is prepared, it is placed for a minute into a vacuum desiccator, in order to remove air bubbles, and then poured over the internal cast mounted within the glass ring. The ring, containing the resin and the specimen, is then transferred to the vacuum desiccator and air bubbles drawn off. If the rock matrix is very porous, the specimen should suffer vacuum treatment for no more than thirty seconds, otherwise some impregnation of the matrix will take place, leading to difficulties during the solution stage ; with most matrices one minute has been found to be the best time for the vacuum treatment. The ring, containing the specimen, is now removed and put to one side for twenty-four hours, at the end of which time the plastic should be set hard. The glass ring is detached from the glass plate and the sides heated with a bunsen burner, after which the specimen and the resin cast can be pushed out of the ring. In most cases the paraffin wax adhering to the rock can be removed with a knife. Failing this, it is immersed in a dish of boiling water for ten minutes, the water allowed to cool, the solid paraffin wax lifted off, and the resin cast, together with the specimen, isolated ; the paraffin wax can be used again. The base of the specimen is ground away, until it is not safe to proceed further, and then placed in hydrofluoric acid contained in a wax bath. From time to time the specimen should be lifted out with wax-coated tongs, washed, and scrubbed either with a toothbrush or with a dental brush fixed to an arm rotated by a small dynamo. When all the matrix has been removed, the surface of the impression is cleaned in the dry or wet state by means of a dental polishing brush and, if desired, the surface can be polished by the use of dental powder.

Any glass apparatus can be cleaned free of resin by washing in a hot solution of 20 per cent to 30 per cent caustic soda, but this must be done shortly after use.

Although the technique herein described refers to the internal casts of brachiopods, it can be employed satisfactorily for internal casts and external moulds, large or small, of most invertebrate or vertebrate fossil. It cannot, however, be applied to matrices containing calcium carbonate, as these are attacked by the acid catalyst used with the resin. Casts or moulds in non-calcareous arenaceous rocks, in hardened argillaceous sediments, and in ironstone nodules, can all be treated successfully. The result is a perfect impression made in a material which is hard, does not shrink and is probably much more permanent than most fossil specimens, since it is not likely to suffer damage through storage or much handling.

The best photographic results are obtained if the impression is coated with a thin layer of ammonium chloride ; sometimes, this method is impracticable or difficult to operate, owing to a humid atmosphere, and we here wish to thank Mr. J. C. Harper, who has given us permission to describe how magnesium oxide can be employed in a similar manner. Magnesium ribbon is burnt at a distance of about 6 inches underneath the object to be photographed, and this results in a thin film of magnesium oxide being deposited over the surface. Delicate detail is retained so long as the film is thin enough but detail is lost if the ribbon is burnt too near the specimen. Material already treated in this way includes ostracods, trilobites, and brachiopods preserved in different kinds of sediment, as well as casts and moulds made in various media and, in all cases, the photographic results have been entirely satisfactory. The magnesium oxide can be removed by wet or dry brushing, or by pressing fresh plasticine against the whitened surface.

The phenol formaldehyde resin will probably be found of value in other geological investigations, in particular as a cement for metalliferous minerals, prior to polishing, and for incoherent sediments ; it would also serve as a mountant for sand grains.

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CORRESPONDENCE

CORRELATION OF LAKI BEDS

Sir,—May I be permitted to reply briefly to Colonel Davies's letter published in your number for May/June, 1940, page 252 ?

It is unfortunate that the Laki section first to be described in detail should have been that of the Meting area in Sind, where the succession is obviously incomplete ; it comprises less than 500 feet of beds, mostly limestones, with pronounced unconformities above and below. *Alveolina* (*Flosculina*) *globosa* occurs in the lower limestone and is absent above, but it is doubtful whether this distinction has any zonal significance. A much more complete development of the Laki is present in Baluchistan and the formation reaches its maximum thickness in the Suleiman foothills. It is with these sections, rather than with the abbreviated section in Sind, that the correlation of the Punjab Laki should first be attempted.

The Laki sections of the Salt Range and the Kohat District are closely similar. In the Salt Range the Nammal Shales, with *Nummulites irregularis* and *Discocyclina ranikotensis*, pass upwards into the Sakesar-Bhadrar limestones containing *Assilina* species formerly grouped with *A. granulosa*, *Nummulites atacicus*, and *Orbitolites complanatus*. These limestones become dolomitic above and pass, apparently without break, into the gypsum and salt deposits of the Lower Chharat. In Kohat, shales with the Nammal fauna pass upwards into the Shekhan Limestone, and this in turn into the Lower Chharat. On the stratigraphic evidence, therefore, the Shekhan Limestone is homotaxial with the Sakesar-Bhadrar limestones. Colonel Davies claims that the Shekhan Limestone is newer than the uppermost Laki of the Salt Range; but if so, where is the equivalent of the Shekhan Limestone in the Punjab and which part of the Kohat Laki represents the Sakesar-Bhadrar beds? The fossil evidence on which Colonel Davies relies seems insufficient in view of the stratigraphy; part of the difference in fauna is due probably to the different conditions of deposition in the two regions (the relationship between facies and the distribution of the foraminifera is a subject as yet much neglected); for the rest, the distinction depends upon newly described species whose geographical distribution and range in time will certainly be extended by further work.

Although the Laki reaches a much greater thickness in the Suleiman foothills, the general succession is closely parallel with that in the Punjab and Kohat. The equivalents of the Lower Chharat can be recognized not only by the presence of gypsum beds and vertebrate fossils, but also by their position at the base of a well-defined Khirthar sequence. These beds pass down with apparent conformity into thick limestones containing *A. granulosa* and *N. atacicus* similar in lithology and stratigraphic position to the Sakesar-Bhadrar beds of the Salt Range. The next lower formation, the Ghazij Shales, attains a thickness of several thousands of feet and is somewhat variable in character. In the north the uppermost beds are estuarine (it is this part of the Laki which extends into South Waziristan) and the lower are for the most part unfossiliferous; farther south, and in the Harnai-Dirgi region, the Ghazij Shales are locally very fossiliferous and contain *N. irregularis* and *Discocyclina archiaci* var. *baluchistanensis* (which is closely allied to and possibly identical with *D. ranikotensis*). Thus, not only do the Ghazij Shales occupy a corresponding stratigraphic position with the Nammal stage of the Punjab, but they also contain a similar fauna.

The Dunghan Limestone underlies the Ghazij Shales continuously for over 600 miles from the Suleiman foothills to the Bolan Pass. In addition to several forms typical of the Laki (including those of the Nammal stage), it contains *Nummulites sindensis* (the *Operculina canalifera* group) which has hitherto been recorded only from the Ranikot. The Dunghan Limestone is cut out from the succession near the southern border of Waziristan by overlap along the unconformity at the base of the Eocene. No representative of it has been recognized in the Punjab or Kohat, where its absence is explained by the unconformity between the Ranikot and Laki. It seems reasonable to conclude, therefore, that the Laki is more completely developed in the Suleiman foothills than farther north, that the Ghazij Shales should be equivalent to the Nammal, and that the Dunghan Limestone is the oldest known Laki in North-West India.

The correlation outlined above is based mainly on the comparative stratigraphy but is also in accordance with the fossil evidence at present available ; much further work remains to be done in this latter connection, and our knowledge of the distribution of the foraminifera is as yet far from complete. The correlation suggested by Colonel Davies is independent of, and frequently in conflict with, the stratigraphy ; on his correlation not only are there no representatives of the Sakesar Limestone in Kohat or of the Shekhan Limestone in the Punjab, but there is similar difficulty in finding equivalents in these regions for the members of the well-marked Laki sequence of the Suleiman foothills.

Colonel Davies's reasons for abandoning the name "Dunghan Limestone" will appear insufficient to most of the geologists who have any knowledge of that formation. The sections in the immediate neighbourhood of Dunghan hill have been critically examined by Noetling and other members of the Geological Survey of India ; collections have been made from Dunghan hill itself. There is no ambiguity in the use of the name and no reason, therefore, to add still further to the already overburdened terminology of the Indian Eocene.

E. S. PINFOLD.

SRINAGAR,
KASHMIR.
2nd October, 1940.

REVIEW

British Hills and Mountains. By J. H. B. Bell, E. F. Bozman, and J. Fairfax-Blakeborough. pp. viii + 120, with 99 plates. London: Batsford, 1940. Price 8*s.* 6*d.*

This is not a book for the geologist; for though occasional notes as to the rocks and structure of the hills are given, these are intended rather for the mountaineer and climber than for the student of the evolution of Britain. But as a guide to the visitor, or by its beautiful and well-chosen illustrations as a help to the teacher of physical geography and geology, it could hardly be improved. From Ben Hope to Brown Willy they are all—or nearly all—here with their features described and their charm indicated, the summits great and small that mean for some of us the best memories of our island. It is an achievement to have surveyed in such small compass so wide an area without descending to the method of a mere catalogue and without omitting the particular heights—be it Welsh peak or Sussex down—that are to each one of us his private shrine.

The Scottish section is probably, and as Scots will claim deservedly, the fullest and most satisfying half of the book—even here the present reviewer looked in vain for Foinaven and Quinag, but rejoiced in the notice of the Merrick and Ben Lawers. Wales suffers from too much compression, and Snowdonia from concentration upon its climbs. The Lake District, too, is described in relation to its " pitches ", and the author fails to catch and describe its peculiar loveliness; there is nothing here to remind us of our moments on Great Gable—the view from which Ruskin described as the most satisfying in Western Europe—or on Helvellyn. The Pennines and East Yorkshire moors are recorded in much less detail; indeed, we could wish for fuller information about their varied and often surprising fascination, the limestone pavements on Ingleborough, the awe of Gordale Scar, the amazing amphitheatre of Malham Cove, the gorge of Newton Dale. But it is ungracious to criticize. The book is good, even if it—and any other that could be written—fails to do full justice to its theme.

C. E. R.

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